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Evidence Synthesis Report: 3

Land Use Review: Fluxes, Scenarios and Capacity

Authors: Eamon Haughey, David Styles, Matthew Saunders, Ruth Bennett Coady and James Moran

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

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2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Land Use Review: Fluxes, Scenarios and Capacity

Evidence Synthesis Report

Prepared for the Environmental Protection Agency

by

Department of Natural Resources and the Environment, School of Science and Computing,
Atlantic Technological University, ATU Galway

Authors:

Eamon Haughey, David Styles, Matthew Saunders, Ruth Bennett Coady and James Moran

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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DISCLAIMER

This report is based on research carried out/data from February to July 2022. More recent data may have become available since the research was completed.

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Project Partners

Dr Eamon Haughey
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
ATU Galway City
Dublin Road
Galway
Tel.: +353 (0)91742154
Email: eamon.haughey@atu.ie

Dr David Styles
Ryan Institute
School of Biological and Chemical Sciences
University of Galway
Galway
Ireland
Email: david.styles@nuigalway.ie

Dr Matthew Saunders
Botany Department
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland
Email: saundem@tcd.ie

Ruth Bennett Coady
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
ATU Galway City
Dublin Road
Galway
Ireland
Email: ruthbcoady@gmail.com

Dr James Moran
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
ATU Galway City
Dublin Road
Galway
Ireland
Email: james.moran@atu.ie

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Executive Summary

In 2020, grasslands were the dominant form of land use in Ireland, accounting for 59.2% of total land use. There were also significant areas of wetlands (17.2%), forest land (11.0%) and croplands (10.4%). Between 1990 and 2020, there was a 51.4% increase in forest land, a 19.9% increase in settlement land and an 8.5% decrease in wetlands, whereas the picture was relatively stable for croplands and grasslands. However, much of the major land use change in Ireland happened prior to 1990, with for example forestry increasing from around 1.4% in 1918 to the present level of around 11%. Meanwhile, wetland and cropland areas have decreased substantially since the middle of the 19th century. A regional analysis of land cover in Ireland has shown strong differences in the distribution of many land cover categories. For example, croplands and infrastructure land (e.g. urban areas and other artificial surfaces) are more dominant in the east and south-east of the country, while the land cover categories most associated with high biodiversity value occur predominantly in the border, west and mid-west regions.

The agriculture, forestry and other land use (AFOLU) sector was a significant source of net greenhouse gas (GHG) emissions in Ireland over the 2016–2020 period, accounting for an average of 27,707 (±888) kt of carbon dioxide equivalents per year (kt CO_2 eq yr^{-1}). The single largest contributor to GHG emissions from agricultural activity was methane (CH_4) from ruminant livestock, followed by nitrous oxide (N_2O) emissions from nitrogen (both organic and inorganic) application to soils, and the deposition of excreta. At the same time, forest land and associated harvested wood products provided an important net sink, which averaged –2957 (±338) kt CO_2 eq yr^{-1} from 2016 to 2020, despite losses of carbon from afforested organic soils. In 2020, although grassland (land use category) on mineral soils provided an estimated net sink of –2291 kt CO_2 eq overall, this was outweighed by emissions of 8432 kt CO_2 eq in 2020 from grassland on organic soils, even though organic soils accounted for only 8.1% of the total grassland area. It is noted that, in line with international conventions, the national GHG inventory currently reports GHG emissions for agriculture and for land use, land use change and forestry (LULUCF) separately and not combined as AFOLU.

Already observed changes to the global climate system include increases in mean temperatures, atmospheric CO_2 concentration, the frequency and intensity of warm or hot extremes, heavy precipitation events, agricultural and ecological droughts, co-occurring droughts and heatwaves, and extreme sea levels; and decreases in cold extremes. Over the period 2081–2100, projected temperature increases for northern Europe range from 2.6°C to 5.4°C under low to high global warming scenarios. At the national level (under a moderate global warming scenario), projections for mid-century indicate increases in annual temperatures of 1.0–1.2°C, a decrease in summer precipitation and an increase in the occurrence of heatwaves, especially in the south and east of the country, as well as an increase in the frequency of heavy precipitation events. A decrease in the number of frost days, with an associated increase in the length of the growing season, is also projected. It is expected that CO_2 fertilisation and an extended growing season will result in increased gross primary production; however, this may be counteracted by an increase in the frequency and severity of extreme events also projected by mid-century. The projected increases in heavy precipitation events by mid-century are likely to have an impact on the trafficability of managed soils, while droughts and heatwaves may lead to carbon losses from peatlands and a higher frequency of wildfires.

To explore the level of change required in agriculture and land use that would be commensurate with a net-zero AFOLU sector by 2050, a set of indicative scenarios were developed. The scenarios were based on the GOBLIN model approach along with a set of simplified baseline assumptions. These scenarios suggest that achieving net-zero GHG emissions in the AFOLU sector by 2050 will be very challenging. Only those scenarios that include all of the following measures are expected to be able to achieve net zero by 2050: effective abatement of livestock emissions (an emissions decoupling of approximately 30%) plus ruminant livestock number reduction (up to 30%

considered); ambitious organic soil rewetting (up to 90% of drained organic soils considered); and large areas of afforestation (up to 875,000 ha of new forest by 2050 considered). This was the case whether AFOLU CH_4 emissions were included in or excluded from the overall GHG balance; however, when CH_4 was excluded and dealt with using a separate target, it was possible to reach net zero with a smaller area of additional forest by 2050 (500,000 ha).

The effective targeting and implementation of climate mitigation measures in the AFOLU sector together with subsequent land management will largely determine whether land use change results in benefits to or substantial trade-offs for biodiversity and water resources. The level of change to the AFOLU sector required to meet net-zero targets under the indicative scenarios developed here would have major consequences for water quality and biodiversity, as well as for many other provisioning and non-provisioning ecosystem services. Continued biodiversity loss has the potential to hamper the effectiveness of mitigation in the AFOLU sector and also to reduce the resilience of ecosystems to climate change extremes. The impacts of large-scale rapid afforestation on water quality, water quantity and biodiversity will vary throughout the forestry management cycle and according to other factors such as the species composition of the area afforested, tree species mix and forestry management decisions. The restoration of degraded peatlands as a climate mitigation measure can have significant co-benefits for biodiversity, water quality and water regulation. However, successful restoration depends on a range of site-specific conditions, including the degree of prior modification of peatlands through drainage, peat extraction and conversion to grassland, cropland or forestry land uses. Measures taken to reduce agricultural emissions including related changes in livestock densities are likely to have complex interactions with biodiversity and water quality. An integrated land use management approach is required to target land use to meet multiple goals cognisant of the trade-offs and synergies between them while balancing environment, social and economic outcomes. Strategic targeting of land use should acknowledge the varying capacity of different land types to provide a diverse range of ecosystem services, from provisioning (e.g. food and fibre), regulating (e.g. climate, water) and supporting (e.g. nutrient cycling) services to cultural (aesthetic, recreational) services. Such an approach can support policymakers, land managers and users to develop and implement land use strategies that meet the needs of society while protecting natural resources.

The land use and climate change policy landscape of the European Union and the Government of Ireland, as well as of state or semi-state agencies in Ireland, is complex and occurs across multiple time horizons. An analysis of key policy documents has indicated that in many cases the stated policy targets were not consistent with the levels of land use change required to meet net-zero targets in the AFOLU sector by 2050, based on the indicative scenarios developed in this report. This was especially apparent for afforestation, for which policy targets were much lower than those used in modelled scenarios. While there is significant scope for climate actions to be deployed across the land system in Ireland, adequate enabling conditions are also required. Important knowledge gaps that hamper rapid progress across multiple sectors include the need for more detailed data on land cover/land use and soil carbon fluxes, uncertainty about climate impacts on the land system and the contribution of areas of semi-natural vegetation to climate mitigation. There is also a need for more effective knowledge sharing and innovation development with land managers to enable effective and timely climate actions.

1 Current Land Cover, Land Use and Trends

The objective of this chapter is to provide an overview of land cover, land use and recent trends in Ireland. Section 1.1 gives an overview of current land use and trends in Ireland, while section 1.2 provides a spatial and regional analysis of land cover data (some limitations of the approaches taken, and available land cover and land use data are discussed in section 6.3.1). It is important to note that this chapter's analysis is focused on recent land cover and use, with available data going back to 1990. However, much of the significant change to land cover and use in Ireland occurred prior to 1990, and this is discussed in section 1.1.6 on historical land use change. In this chapter, land cover is defined as the biophysical coverage of land (e.g. bare rock, forest or infrastructure), while land use is defined as the total of arrangements, activities and inputs applied to a parcel of land (adapted from IPCC, 2019b). Land cover is often categorised into broad classes (such as artificial, agriculture, forest and semi-natural land cover), and this categorisation is usually based on satellite data. We note that land cover categorisation varies significantly across datasets globally. However, land use is most often classified according to internationally accepted categories such as those used for greenhouse gas (GHG) reporting in national inventories under the United Nations Framework Convention on Climate Change (UNFCCC). Another key concept with regard to land use is land use change, which involves change from one land use category to another under the GHG inventory framework. This is distinct from changes in land management, such as increasing or decreasing the intensity of land use, on land that remains in the same category.

1.1 Current Land Use and Recent Trends

Land use in Ireland is dominated by grassland (Figure 1.1), which in 2020 accounted for 59.2% of all land use (EPA, 2022a). This was followed by significant areas of wetlands (17.2%), which include peatlands and other wetland systems, forest (11%), cropland (10.4%), settlement (1.8%) and other land (0.4%).

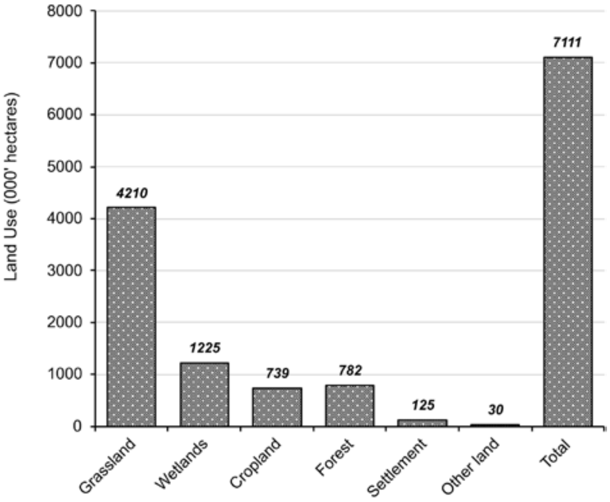

Figure 1.1. Land use in Ireland in 2020. Data source: EPA (2022a).

1.1.1 Grassland

In 2020, grassland was the largest land use category, at 59.2% (Figure 1.1). Beef cattle, dairy production and sheep farming are the primary uses for grassland in Ireland, and the associated outputs make up the largest share of the total economic value of the agri-food sector (Haughey, 2021). The current Atlantic-temperate climatic conditions in Ireland permit a relatively long grazing period, which enables a high level of grazed grass intake. This reduces the need for supplementary feed, which is economically favourable because it lowers feed costs and confers a competitive cost advantage on grazed pasture systems in Ireland (Dillon, 2018; Finneran *et al.*, 2012). It is noteworthy that there are large regional differences in the intensity of management and use across a range of grassland types, related to differences in climate, topography, soils and vegetation composition (see section 1.3.1). Differences in the intensity of agricultural activities are also driven by variations in fertiliser use and stocking rates across grassland-based farming systems.

In terms of trends in the area under grassland use, the picture is relatively stable, with grassland as the dominant category between 1990 and 2020 (Figure 1.2). There has been a small decrease in the grassland area, commensurate with increases

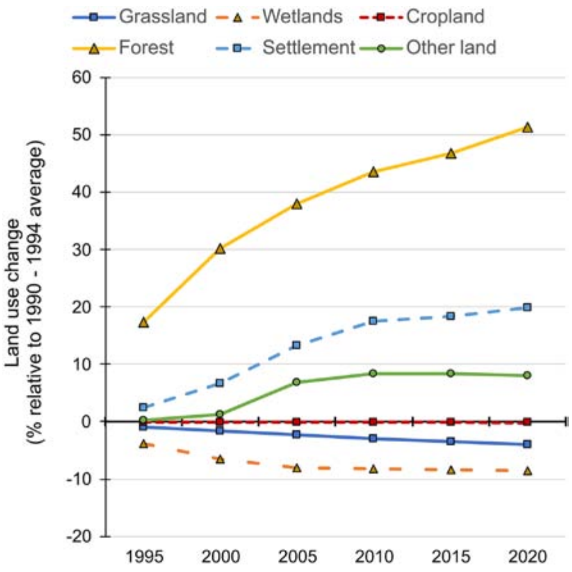

Figure 1.2. Land use change in Ireland relative to 1990–1994 average (%). Note that values for 1995, 2000 and 2005 are 5-year averages. Data sources: CSO (2021) for 1990–2015 data and EPA (2022a) for 2020 data.

in other land uses such as settlement and forestry. However, compared with large declines in permanent grassland in other parts of Europe, estimated at a loss of 5.9 million hectares between 1970 and 2013 (Dillon, 2018), the grassland area has been relatively stable in Ireland.

1.1.2 Wetland

The second largest land use category in 2020 was wetland, at 17.2% (Figure 1.1); this category is predominantly made up of peatlands. Peatlands in Ireland are sub-classified into three main categories: blanket bogs, raised bogs and fens (Renou-Wilson, 2018). Blanket bogs typically occur along the west coast and on hilltops and mountaintops across the country and have an average depth of around 2.5 m. Raised bogs are more typically located in the midlands and are much deeper than blanket bogs, with an average depth of 6–7 m (Renou-Wilson, 2018). Both blanket and raised bogs may be described as ombrotrophic peat soils, where the water maintaining these systems is derived from precipitation, while fens, which are fed by groundwater, are described as minerotrophic and are less common (Creamer and O’Sullivan, 2018). As well as providing a very substantial carbon store, peatlands provide other important regulating and cultural services, such as water filtration and storage, biodiversity and tourism (Bonn *et al.*, 2016). Peatland in Ireland has historically been exploited and degraded through drainage for agriculture, forestry and extraction. Where this conversion has taken place, the former wetland, which is usually drained for other activities, is now categorised under the relevant land use category (i.e. grassland or forestry). This has implications for the GHG flux associated with land use, land use change and forestry (LULUCF) in Ireland.

The share of land use accounted for by the wetland category decreased from 18.8% in 1990–1994 to 17.2% 2020, an 8.5% reduction (CSO, 2021; EPA, 2022a). Most of this decrease occurred during the 1990s, with the area stabilising in the last 10 years (Figure 1.2). The larger change from 1990 to 2005 is related to the conversion of wetland to forestry and settlement land uses. However, it is noteworthy that much of the land use change associated with the wetland category occurred prior to 1990 (see section 1.1.6).

1.1.3 Forest land

In 2020, forests made up 11% of land use in Ireland (Figure 1.1). Forestry plantations in Ireland are dominated by conifers, and Sitka spruce (*Picea sitchensis*) is the most common tree species, accounting for 44.6% of the total forest area (DAFM, 2022a). Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), larch species (*Larix* spp.) and other conifer species make up a further 18.8%, with the remaining 27.0% of currently stocked forest area being under broadleaved species (DAFM, 2022a). It is notable that, at 11%, the proportion of forest land in Ireland is much lower than the EU average, which was 32.6% in 2015 (EUROSTAT, 2015). However, these statistics should be considered over a longer time frame for context: the area of forest land has increased dramatically over the last century, from a low of 1.4% in 1918 to current levels (see section 1.1.6).

The largest land use change in Ireland over the last three decades has been in forestry, whose share increased by 51.4%, from 7.3% of land use in 1990–1994 to 11% in 2020 (CSO, 2021; EPA, 2022a). Notwithstanding increases over the last century, the annual rate of afforestation has slowed since 2010 (Figure 1.2). This represents a decline in afforestation rates of over 80% since their peak in the 1990s

(DAFM, 2022a). In Ireland, forest land is defined "as land with a minimum area of 0.1 ha under stands of trees 5 m or higher, having a minimum width of 20 m and a canopy cover of 20% or more within the forest boundary; or trees able to reach these thresholds in situ" (DAFM, 2018a). Note that this definition relates to only land use and not land cover, and it also means that open space within a forest boundary either permanently or temporarily unstocked with trees, along with felled areas that are awaiting regeneration, is considered forest land.

1.1.4 Cropland

Cropland accounted for 10.4% of land use in 2020 (Figure 1.1), with barley, wheat and oats being the three main cereal crops grown in Ireland in that year (DAFM, 2021a). At farm level, specialist tillage farms and mixed crop and livestock farms accounted for 3.4% and 1.3% of the total number of farms in 2020, respectively (CSO, 2020). The cropland area was relatively stable over the 1990–2019 period (Figure 1.2). However, agricultural activity occurring in the cropland category is more dynamic than is suggested by the overall change in cropland area. Although relatively large areas may enter and leave the cropland land use category on an annual basis, the overall area on balance remains unchanged (Zimmermann *et al*., 2016). The majority of this land use change involves conversion of existing cropland to grassland, and vice versa. However, of the land area being converted from cropland use, around 70% is returned to cropland within 5 years (Zimmermann *et al*., 2016). This change in land use is important, since the conversion of grassland to cropland is associated with a loss of carbon from soils. The amount of time the land remains "temporary grassland" impacts the potential of soils to regain carbon that was lost during the cultivation phase. This also highlights the need to collect detailed temporal data on land use and land use change (see section 6.3.1).

1.1.5 Settlement and other land

In 2020, settlement and other land accounted for 1.8% and 0.4%, respectively, of land use in Ireland (EPA, 2022a). Data from EUROSTAT indicate that in 2018 the area of residential and services land in Ireland was 3.9%, substantially lower than the EU average of 5.7% (EUROSTAT, 2021). According to national Central Statistics Office (CSO) data, since 1990–1994 there has been an increase of 19.9% in the share of land used for settlement, from 1.5% of total area in 1990–1994 to 1.8% in 2020 (CSO, 2021; EPA, 2022a). These differences in the EUROSTAT and CSO data are due to variations in the land use categorisation methods used. The rate of land conversion to the settlement category has plateaued since 2010 (Figure 1.2), which is strongly linked to the economic downturn at that time.

Globally, the development of urban settlements and infrastructure, including transport networks, industrial areas and mines, has increased dramatically in the last hundred years. The development of infrastructure is often associated with soil sealing, which is defined as the covering of the ground with an impermeable material. The European Commission recognises that soil sealing is a major driver of soil degradation in the EU that often affects fertile cropland, negatively impacts on biodiversity and increases the risk of flooding and water scarcity (European Commission, 2019). Since the mid-1950s, the total surface area of urban centres in the EU has increased by 78%, while the population has grown by only 33% over the same period, indicating an increase in per-capita urban area utilisation. The urban population in Ireland is substantially smaller than the global average of 76% and the European average of 70.1%, with only 54% of the Irish population classified as urban dwellers in 2015 (Carneiro Freire *et al*., 2019).

1.1.6 Historical land use change

The analysis of land use change conducted in this report is focused on the period from 1990 to the present because of the availability of spatial data records. However, many of the significant changes to land use and cover in Ireland occurred prior to 1990. In the case of forestry, there has been significant change over the last century and indeed over the last millennium. The area of forestry land has increased very significantly in the last hundred years in Ireland, from around 1.4% in 1918 to 11% in 2020 (DAFM, 2021c; EPA, 2022a) (Figure 1.1). In the early part of the 20th century, the vast majority of forestry planting was undertaken by the state. However, in recent decades there has been a substantial increase in the area of privately owned forest, from 81,958 ha in 1973 to 411,484 ha in 2022 (DAFM, 2022a). Looking back over an even longer time frame reveals other significant trends in forestry and woodland. Driven by factors including the expansion of human land use and the impact of geographical isolation, historical forest cover had been in a state of decline in Ireland for several millennia (Mitchell, 2000). It has been estimated that up to 64.5% of the usable land (defined as the land available for clearing for agriculture) on the island of Ireland was forested in the year 1000 BCE (Kaplan *et al*., 2009). This area was estimated to have declined to 38% cover by 1000 CE and further to only 19% cover by 1400 CE, which was in line with declines in other parts of western Europe. Similar to England and Wales, but in contrast to other western European areas, the reduction in forest cover on the island of Ireland continued steeply to just under 1% cover by 1850 CE (Kaplan *et al*., 2009).

There has also been significant change to areas of wetlands over the last 100 years. Depending on wetland type, estimates of the reduction in extent range from 50% to 95%. Finlayson and Spiers (1999) estimated that from 1900 to 1999 there was a 50% reduction in the extent of wetlands worldwide, the largest driver of which was conversion to agricultural land. However, the authors of that review also noted that there were relatively large uncertainties associated with this estimate due to the diversity of methodologies used to quantify wetland loss and a general lack of spatial time series data. Wetland loss in Europe is estimated to be even more stark, at an 80% reduction over the last millennium, but with a greater share of this loss happening in the last century (Verhoeven, 2014).

In Ireland, peatlands have been used for traditional fuel since prehistoric times. However, it is likely that the impacts of this usage on the extent of the national peatland area were limited until the 19th century (Renou-Wilson, 2018). The use of peat as the primary fuel among a rapidly growing population in Ireland over the first half of that century resulted in the disappearance of peatlands from parts of the east of the country and accelerated loss elsewhere. However, it was the development of modern machinery and the associated industrial extraction of peat from the 1950s onward that had the largest impact on peatland decline (Renou-Wilson, 2018). During the period 1945–1950, the Office of Public Works (OPW) undertook significant arterial drainage work across Ireland, draining approximately 250,000 ha of land (Ryan, 1986). The demand for additional land for agriculture was the main driver, which is understandable in the light of the impact of the Second World War on food security in Europe and Ireland. It is expected that a large proportion of the land drained for agriculture at this time was peatland. Of the maximum extent of peatlands in Ireland over the last 11,700 years, only 15% of the original area is now in near-intact condition (Wilson *et al*., 2013).

The cropland area in Ireland has also undergone significant reduction over the last 200 years. In 1851 there was a peak in the area of land used for “crops, fruit and horticulture”, at 1,420,000 ha (CSO, 1997). Since 1847 there has been a spectacular decline in the area of main tillage crops, with the 1996 estimate accounting for just 26% of the 1851 area (CSO, 1997). The rapid decline in the cropland area over the second half of the 19th century is understandable given the massive reduction in population on the island of Ireland due to the Great Famine and mass emigration. According to Freeman (1954), only 12.2% of the improved land in Ireland was tilled in 1931; however, this increased to 16.4% by 1939 during a period of tillage area expansion. The impact of the compulsory tillage measures introduced by the government during the Second World War further increased the area of tilled land, reaching 21% by 1951. In 2020 there was approximately 739,000 ha of cropland (Figure 1.1), which represents a significant reduction from the 19th century peak; however, we note that because of the different land use definitions used over this period a direct comparison here is not appropriate. However, what is clear is that there has been a dramatic reduction in the cultivated area of Ireland over time.

1.2 Analysis of Land Cover Data as a Proxy for Regional Land Use Trends

The CORINE database comprises satellite-derived land cover data with a spatial coverage spanning Europe. In this report, CORINE (2018) land cover data were used as a proxy for land use or land use potential in Ireland with the intention of providing a high-level overview of the spatial regional dynamics in the current land system. In general, land cover datasets are limited with regard to inference of land use and land use intensity in Ireland, especially at a land management scale, which is reflective of individual farms (O’Donoghue *et al*., 2015). However, at larger scales land cover data can still provide valuable insight into land use and spatial distribution.

1.2.1 Land cover categorisation and data analysis

Initially the total CORINE dataset was reduced to only the major land-related cover classes that are of primary interest to this report. This required the exclusion of the land cover class *waterbodies* (including inland waters and marine waters), which were not part of the primary scope of this report. This resulted in four main classes along with associated sub-classes of land cover. The details of these, along with CORINE database coding, are given in Table A1.1.

The four existing CORINE classes of land cover were:

1. artificial;
2. agriculture;
3. forest and semi-natural;
4. wetlands.

Following this, a category mapping exercise was conducted to create a categorisation of land cover that provided a more useful proxy measure for land use and so enabled more direct analysis of land interaction with GHG fluxes. This categorisation was based approximately on that of Arneth *et al*. (2019) and the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land (SRCCL) (IPCC, 2019c). As a result of this category mapping exercise, seven main land cover classes were identified (for a detailed breakdown, see Table A1.1):

1. grassland;
2. cropland;
3. other agricultural land;
4. forest and woodland;
5. wetland and peatland;
6. other natural land;
7. infrastructure.

Based on this categorisation, a land cover map was produced (Figure 1.3). Subsequently, the spatial

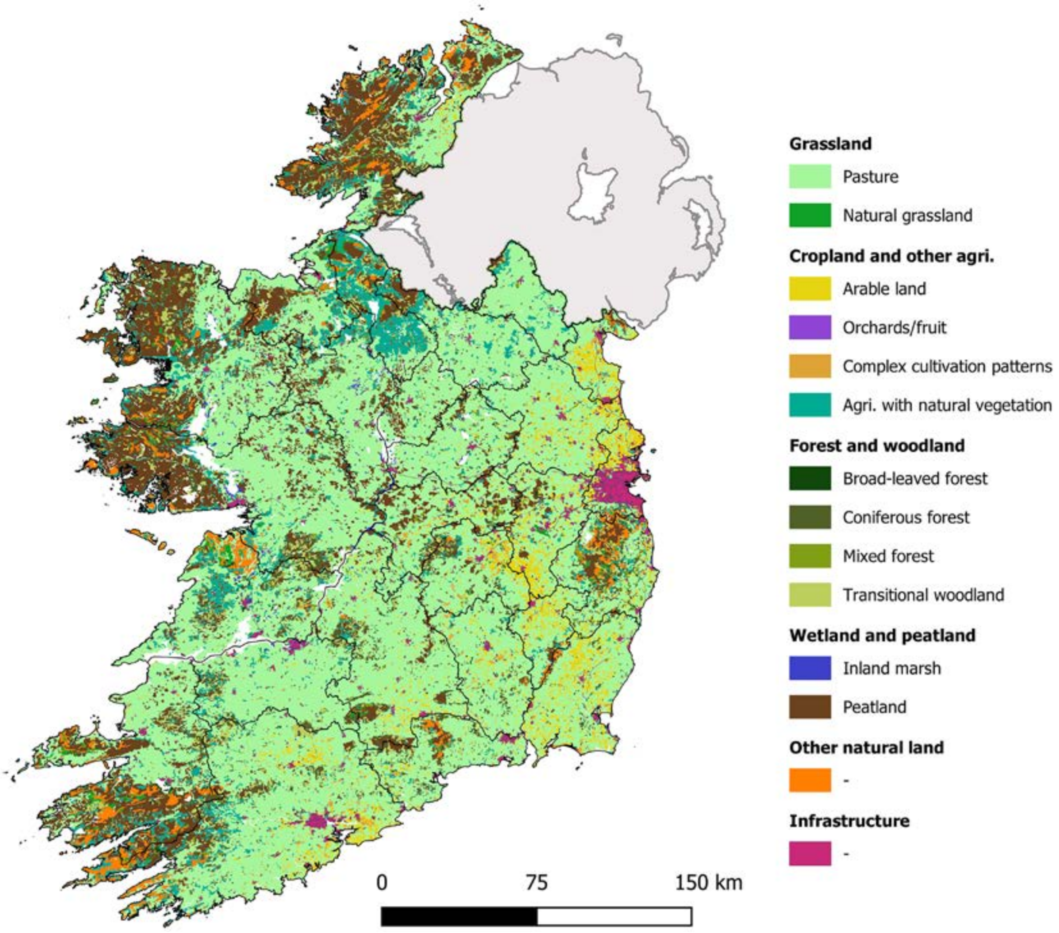

Figure 1.3. Main and associated sub-classes of land cover in Ireland as grouped in this report. Compiled using CORINE (2018) data. A summary of the area extent of each category is given in Table A1.1.

data were extracted using QGIS geographical information software (QGIS, 2022), and the area data are summarised by category. The full details of the extracted data are shown in Table A1.1. A graphical summary of the extracted data shows the total areas for each of the categories (see Figure 1.4).

1.2.2 Regional-level analysis of land cover categories

The Nomenclature of Territorial Units for Statistics (NUTS) is a mapping classification used by the EU that categorises national territories in a hierarchical manner (EUROSTAT, 2018). For example, at the highest level (NUTS1) Ireland is classified as a single unit, while at the secondary level (NUTS2) there are three regions: northern and western, eastern and midland, and southern. Further subdivision at the third level (NUTS3) gives eight regions (see Figure 1.5). Here, to enable a regional analysis of the categorised land cover data (Figure 1.3), regional land cover data were obtained by overlaying the NUTS3 map and then extracting data. The analysis was conducted using QGIS geographical information systems software (QGIS, 2022). The results of this analysis giving a breakdown of the area of each land cover category by region are shown in Table 1.1. An inverse analysis with the percentage area of each region per land cover category is given in Table A1.2.

1.3 National and Regional Land Cover

1.3.1 Grassland cover

Land cover in Ireland is dominated by grasslands (57.5%). The vast majority of these are classified in CORINE as pasture (56.8%), with only 0.7% classified as natural grassland (Figure 1.4). However, the pasture category comprises a spectrum of land use intensity across different soil and climatic envelopes from intensively managed pastures to semi-natural habitat (see section 6.3.1). Grassland cover is relatively evenly distributed across the country (Figure 1.3). A total of 52.5% of the grassland cover area occurs in the mid-west, south-west and west regions (Table 1.1). The regions containing the smallest portion of national grassland cover are the mid-east and Dublin and the midlands, at 10.8% and 11.5%, respectively. Like the distribution of grassland

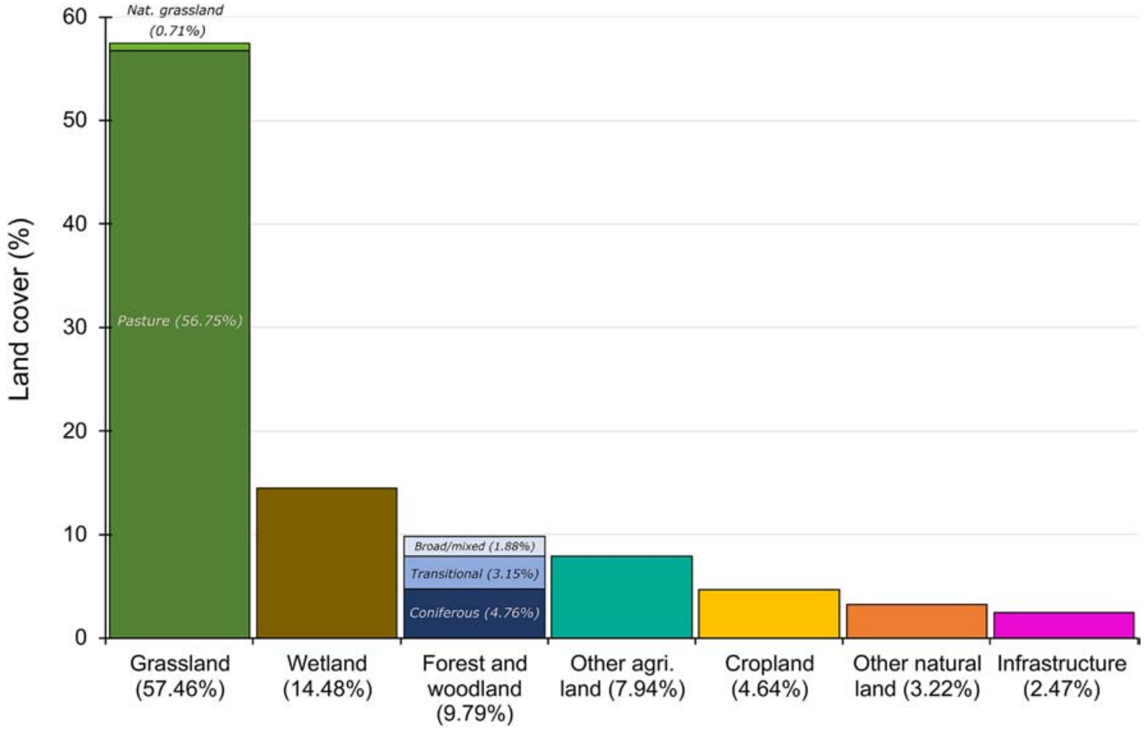

Figure 1.4. Land cover summary for Ireland based on the seven land cover classes. Compiled using CORINE (2018) data. Other agricultural (agri.) land includes complex cultivation patterns, agriculture with areas of natural vegetation, orchards and fruit production. Other natural land includes moors and heaths, beaches, rock, sparsely vegetated areas and burnt areas. Infrastructure includes urban fabric, industrial areas, transport and recreational areas.

NUTS 2	NUTS 3	County
Northern & Western	Border	Donegal Sligo Leitrim Cavan Monaghan
	West	Galway Mayo Roscommon
Southern	Mid-West	Clare Tipperary Limerick
	South-East	Waterford Kilkenny Carlow Wexford
	South-West	Cork Kerry
Eastern & Midland	Dublin	Dublin
	Mid-East	Wicklow Kildare Meath Louth
	Midlands	Longford Westmeath Offaly Laois

Figure 1.5. Nomenclature of Territorial Units for Statistics (NUTS) for Ireland. Source: CSO (2014). Map boundaries are generalised to 100 m. Note that for the purposes of spatial analysis at the NUTS3 level the mid-east and Dublin regions were combined.

Table 1.1. Regional breakdown of land cover categories as a proportion (%) of the total area of each category (using the NUTS3 classification)

	Regional distribution of land cover categories (%)							
Category	Border	Mid-east and Dublin	Midlands	Mid-west	South-east	South-west	West	Category total area ('000 ha)
Infrastructure	9.1	40.9	6.7	10.8	9.7	14.1	8.7	168.7
Croplands	1.3	40.5	8	6.3	30.1	13.4	0.4	320.2
Other agricultural land	32.6	6	5.6	12	4.8	17.7	21.3	544.8
Grasslands	12.8	10.8	11.5	18	12.4	17.3	17.2	3942.1
Forest and woodland	17.1	9	9.9	17.9	9	18.6	18.5	672.2
Other natural land	23.8	11.3	0.3	9.2	4.6	32.1	18.7	217.4
Wetlands (including peatlands)	25.7	3.5	6.7	5.5	1.4	17.4	39.8	992.7

Other agricultural land includes complex cultivation patterns, agriculture with areas of natural vegetation, orchards and fruit production. Other natural land includes moors and heaths, beaches, rock, sparsely vegetated areas and burnt areas. Infrastructure includes urban fabric, industrial areas, transport and recreational areas. See Table A1.1 for area breakdown by category.

cover itself, the distribution of grassland-based agriculture is relatively even across regions. However, this does not take into consideration the types of grassland-based agriculture or the intensity of land use.

The distribution of cattle-based farm enterprises is not evenly spread across the country; in 2020, 63% of beef production specialist farms were located in the border, west and mid-west regions (Table A1.3), whereas dairy farm specialist farms were more common in the southern half of the country, with the mid-west, south-east and south-west regions together accounting for 71.6% of the total (Table A1.3). Sheep production is also not distributed evenly across regions, with 64.1% of the sheep population in 2021 located in the border, west and south-west regions (Table A1.4). The Dublin and mid-east region was also important; a further 15.1% of sheep were located there in 2021 (Table A1.4), a large proportion of which were based in County Wicklow.

Overall, this has implications for the regional distribution of livestock density as well the level of nutrient inputs in terms of both organic and chemical fertilisers. In 2020 dairy farms in Ireland had on average a higher livestock density than beef farms, at 2.05 and 1.27 livestock units per hectare, respectively (Dillon *et al*., 2021).[1] Dairy farms also had a higher average nitrogen balance[2] per hectare, at 184 kg surplus $\mathrm{N\,ha^{-1}\,yr^{-1}}$, compared with 64.9 kg surplus $\mathrm{N\,ha^{-1}\,yr^{-1}}$ for beef farms over the 2018–2020 period (Buckley and Donnellan, 2021). The intensity of sheep farming operations in 2020 was on average similar to that of beef cattle rearing systems, with a slightly lower average stocking density at 1.17 livestock units per hectare (Dillon *et al*., 2021), and an average nitrogen balance per hectare of 56.4 kg surplus $\mathrm{N\,ha^{-1}\,yr^{-1}}$ (Buckley and Donnellan, 2021).

1.3.2 Wetland cover

The wetland category accounts for 14.5% of total land cover (Figure 1.4), with inland marshes making up 0.4% and peatlands 14.1% of that area (Table A1.1). Regionally the distribution of wetland cover is not even, with the border, west and south-west regions accounting for 82.9% of the total wetland area between them (Table 1.1). By contrast, only 1.4% of the wetland area is in the south-east. Although the midlands and mid-west account for only 6.7% and 5.5% of wetland cover, respectively, these areas are likely to contain the majority of raised bog (Renou-Wilson, 2018), which has implications for the distribution of total carbon stocks across the peatland area nationally.

1.3.3 Forest and woodland cover

The forest and woodland category accounts for 9.8% of land cover; 4.8% is accounted for by coniferous forest and 3.1% by transitional woodland and scrub, with the combined broadleaved and mixed forest sub-classes accounting for the remaining 1.9% (Figure 1.4). The transitional woodland cover category can represent bushy or herbaceous vegetation with scattered trees, and this can indicate woodland degradation or recently replanted forestry. The largest share of forest and woodland land cover is in the border, west, mid-west and south-west regions, accounting for 72.1% of the total forest and woodland area, with a substantially smaller area of forest land cover in the south-east (Table 1.1). It is noted that the land cover figure for forestry and woodland is considerably lower than the 11% of forestry land use (Figure 1.1). This inconsistency is likely to be due to difficulties in differentiating between recently felled and replanted forestry land. Technically, this land remains in the land use category of forestry, but that would not be apparent in the available satellite-based land cover data.

1.3.4 Other agricultural land cover

The other agricultural land category accounts for 7.9% of the total land cover (Figure 1.4) and includes complex cultivation patterns, agriculture with areas of natural vegetation, orchards and fruit production. Among these categories, the vast majority of the area is recorded as agriculture with areas of natural vegetation (7.1%; see Table A1.1). In the CORINE system this represents "… land occupied by agriculture with areas of natural or semi-natural origin (including wetlands and water bodies, rock outcrops)" (Bossard *et al*., 2000). In the context of the land system in Ireland it is likely that most of this area represents a mixture of grassland and scrub. Orchards and complex cultivation patterns account for only a combined 0.9% of the total land area, with less than < 0.01% recorded as orchard (Table A1.1). Complex cultivation patterns represent "juxtaposition of small parcels of annual crops, city garden pastures, fallow land and/or permanent crops with scattered houses or gardens" (Bossard *et al*., 2000).

The distribution of other agricultural land is dominated by three regions, border at 32.6%, west at 21.3% and south-west at 17.7%, with the remaining 28.4% spread across the other four regions (Table 1.1). This high level of complex agricultural land has significant overlap with semi-natural areas and is highly relevant to biodiversity and space for nature in these regions. It is also worth noting that these regions have lower shares of intensively managed agriculture in the form of cropland

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[1] Average livestock unit data are from the Teagasc National Farm Survey. It is noted that this is based on a survey of representative farms across the country and not averaged across all farms. For details of the methodology, see Dillon *et al*. (2021).

[2] Nitrogen balance is calculated as nitrogen inputs less nitrogen outputs on a per-hectare basis at the farm gate level. This can provide an indication of the potential magnitude of nitrogen surplus, which reflects the risk of nutrient losses to water bodies, all other things being equal (Buckley and Donnellan, 2021).

cover and are likely to have lower levels of intensively managed grassland; however, that cannot be confirmed with the currently available land cover data. This has consequences for other ecosystem services and their distribution across the landscape. A predicted map of high nature value farmland for Ireland largely confirms the overlap between high nature value land and complex agricultural land cover (Matin *et al.*, 2016).

1.3.5 Cropland cover

In Ireland, cropland cover (defined as arable non-irrigated) makes up 4.6% of the total (Figure 1.4). There are notable regional differences in cropland cover, with 40.5% in the mid-east and Dublin region and a further 30.1% in the south-east (Table 1.1). By contrast, only 1.3% and 0.4% of cropland cover is recorded in the border and west regions, respectively. It is also notable that the cropland cover value is less than half that of the cropland under land use (Figure 1.1). This inconsistency is probably because a large portion of cropland is under temporary pasture cover and so the land cover satellite picks this up as grassland. Small areas of cropland cover are also possibly recorded under the other agricultural land category.

1.3.6 Other natural land cover

Generally, natural land is defined as land with minimal human influence. Here, the “other natural land” cover category used in Figure 1.3 includes moor and heathland, sparsely vegetated areas, and bare and burnt areas. In this analysis the placement of moor and heathland in the other natural land category rather than the wetland land cover category was based broadly on the habitat classification approach of Fossitt (2000). Combined, these areas account for 3.2% of the total land cover (Figure 1.4). There are strong regional differences in the distribution of other natural land cover, with 74.6% occurring in the south-west, border and west regions (Table 1.1). It must be noted that several of the other land cover categories also include areas of what could be described as natural land or land with minimal human influence, notably natural grassland at 0.7% and agriculture with areas of natural vegetation at 7.1% of total land cover (Table 1.1). In addition, the wetland category of land cover includes some, albeit a small proportion of, intact peatlands and salt marshes that could be described as natural lands.

The classification of natural land and its relation to land use and land cover is complex, and data sources are compiled using various approaches. In Ireland the area of “other” land use, which is land use other than grassland, forest, cropland, wetland and settlement, made up 0.4% of the total in 2020 (Figure 1.1). This classification of land use is in line with the IPCC land use categories of forest land, cropland, grassland, wetlands, settlements and other lands, which are used for national GHG inventory purposes. However, it is not clear what proportion of the “other lands” contains natural land.

1.3.7 Infrastructure cover

In terms of land cover, CORINE 2018 data indicate that infrastructure makes up 2.5% of the total (Figure 1.3). This category includes urban areas, transport such as roads, rail, ports and airports, industrial areas, and recreational land cover. There are strong regional differences in the distribution of infrastructure, with over 40% found in the mid-east and Dublin region (Table 1.1).

Using CORINE data, Ahrens and Lyons (2019) examined trends in land cover and urbanisation in Ireland between 1990 and 2012. Over that period Ireland experienced a higher rate of conversion to infrastructure than the EU average, although the rate of urbanisation did decrease from 2006 to 2012. In terms of types of land conversion, grassland and cropland were the main land cover types converted to infrastructure, with only small areas of forestry and wetland converted. Importantly, the authors also found that Ireland has a significantly higher proportion of urbanisation in areas of low population density than the EU average. This is indicative of a higher level of urban sprawl and is likely to be linked to the lower-than-average proportion of the population who live in urban areas. Urban sprawl is not easily defined as it involves spatial and temporal trends. It is most broadly defined as an inefficient spatial pattern of urban expansion (Ewing, 1997); it may be defined more specifically as “low density or single-use development; scattered or leapfrog expansion; excessive spatial growth; segregated land use; and auto-dependency” (Tian *et al.*, 2017). The potential negative impacts of urban sprawl are diverse, ranging from a loss of natural or agricultural land to negative environmental impacts from inherent inefficiencies in service provision.

2 Greenhouse Gas Fluxes from Agriculture, Forestry and Other Land

The objectives of this chapter are to provide an overview of land-related GHG fluxes in Ireland. In the context of national GHG inventories as defined under the UNFCCC, emissions from the agriculture sector are related to activities that occur on agricultural land, such as the management of livestock and the application of fertilisers to soils. However, this is distinct from the land use and land use change GHG fluxes recorded under the LULUCF category. In that case, for example, carbon sequestration in soils and biomass on agricultural land and emissions from drained peatlands would be included. In this report the agriculture and LULUCF categories are dealt with in combination using the agriculture, forestry and other land use (AFOLU) category, which is defined as “the sum of the GHG inventory sectors Agriculture and Land Use, Land-Use Change and Forestry (LULUCF)” (IPCC, 2019b). The AFOLU category is particularly useful when seeking to prioritise ways in which the land sector can contribute to climate change mitigation. However, under UNFCCC reporting, national inventories are required to be prepared using separate agriculture and LULUCF categories. Separately, the European Commission has proposed using an AFOLU sector post 2030 as part of its “Fit for 55” package, which indicates that international GHG inventory reporting standards may change in the future (European Commission, 2021a).

In relation to climate mitigation, Ireland’s AFOLU GHG emissions profile is particularly challenging, given the high level of agricultural emissions from ruminant livestock as well as large net emissions from land use and forestry. This chapter provides a disaggregated analysis of GHG fluxes for the AFOLU sector in Ireland. The approach taken has been to assess GHG fluxes in CO_2eq based on standard inventory reporting practices that use the global warming potential (GWP) metric GWP_{100}. To account for and explore interannual variation in emissions, where possible, 5-year (2016–2020) average values and their variance are quoted (based on national GHG inventory data, as compiled by the EPA).

2.1 Overall Agriculture and LULUCF Greenhouse Gas Flux

Over the 2016–2020 period, the average annual emissions from the agriculture sector were estimated at 20,620 (±525) kt CO_2 eq yr^{-1} (Figure 2.1). Agriculture accounts for the largest share of national GHG emissions in Ireland, amounting to 37.1% in 2020[3] (EPA, 2022b). The large contribution of agricultural activity to national emissions has been relatively consistent since the reporting of GHGs began in 1990, when agriculture accounted for a 35.5% share. The dominance of agricultural emissions in Ireland is an outlier compared with other EU countries (Haughey, 2021). In 2020, agriculture, including LULUCF, accounted for 11.8% of net GHG emissions across the 27 EU Member States (EEA, 2021). This is attributable to a combination of large ruminant livestock numbers, which correspond to the dominance of grassland as the main land use, and a relatively low level of heavy industry in Ireland.

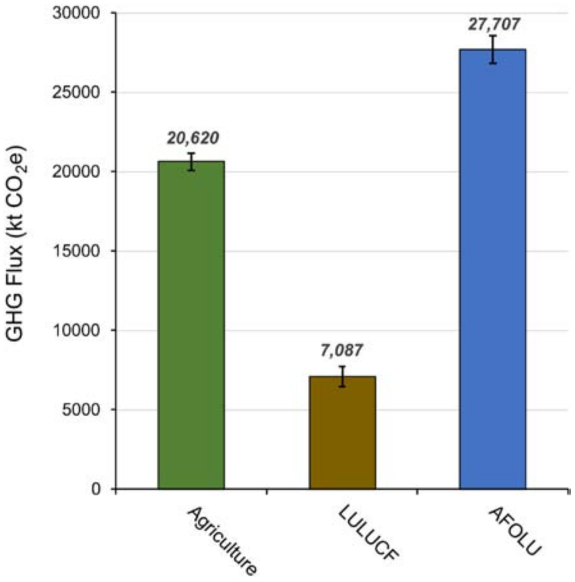

Figure 2.1. Annual average (2016–2020) GHG flux for agriculture, LULUCF (sum of sinks and sources) and AFOLU (combined balance of the agriculture and LULUCF categories) in Ireland (±1 SD).

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[3] Note that this total excludes LULUCF.

Because of the complexity of the land system and its interactions with climate and human management, calculating estimates of GHG fluxes for LULUCF is inherently challenging (Jia *et al*., 2019). The LULUCF category is unusual in that it can be both a source and a sink of emissions due to carbon sequestration in soils and biomass. Therefore, LULUCF is generally described in terms of sinks, sources and the net balance of GHG fluxes taking place. Between 2016 and 2020 the annual average balance of GHG sources and sinks for LULUCF was a net source at 7087 (±658) kt CO_2 eq yr^{-1} (Figure 2.1). It is noteworthy that, relative to the total, the variance across years was considerably higher for LULUCF than for the agriculture sector. This overall balance includes an important net sink in the forestry and harvested wood products (HWPs) categories; however, these were outweighed by the combined GHG emissions from grassland and wetlands.

When examined in terms of change from 1990 to 2020 there was some interannual variability in LULUCF emissions, driven by forestry harvesting cycles and the occurrence of wildfires, with croplands fluctuating from a relatively small sink in some years to a small source in others (EPA, 2022a). However, overall, the LULUCF category in Ireland has remained a significant source of emissions consistently since at least 1990. When combining the agriculture and LULUCF categories, the AFOLU sector was a net source of 27,707 (±888) kt CO_2 eq yr^{-1} (Figure 2.1) between 2016 and 2020.

2.2 Enteric Fermentation

Enteric fermentation is the single largest source of emissions from the AFOLU sector in Ireland, with an annual average of 12,175 (±249) kt CO_2 eq yr^{-1} between 2016 and 2020 (Figure 2.2). These emissions are in the form of methane (CH_4; see Information Box 2.1), which is produced during the process of enteric fermentation that occurs as part of the normal digestive process in ruminant livestock (such as cattle and sheep). In this process, methanogenic bacteria in the animal's rumen break down plant material, producing CH_4 as a by-product that is then expelled,

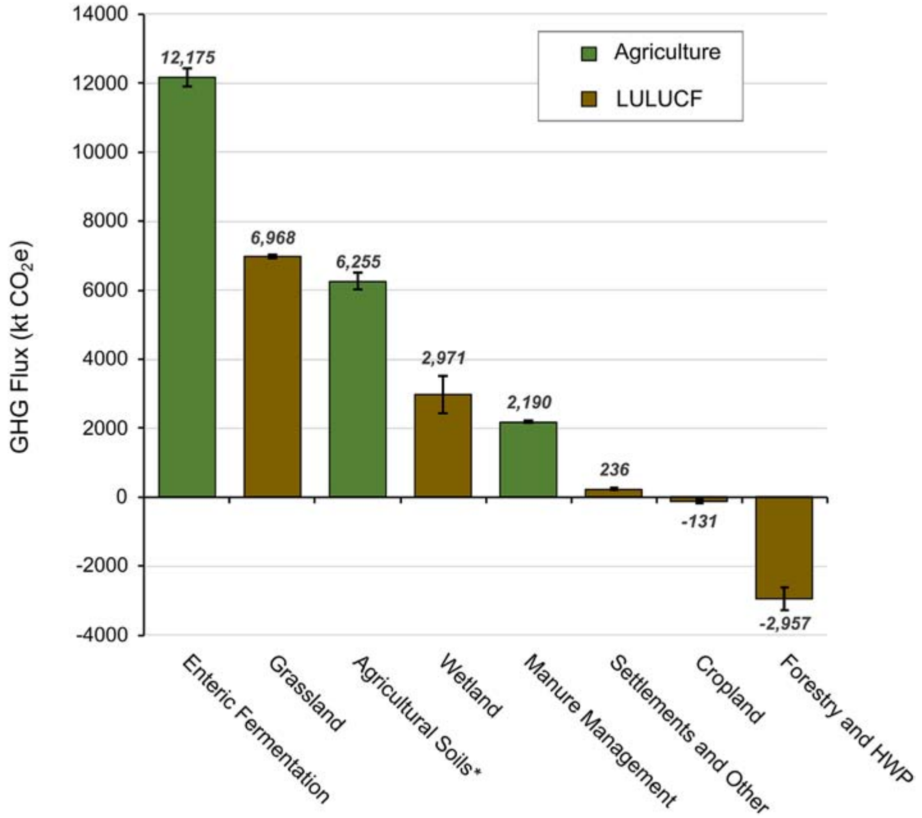

Figure 2.2. Annual average (2016–2020) GHG fluxes for agriculture and LULUCF for Ireland (±1 SD), where "Forestry and HWP" is the sum of the forest land and harvested wood products categories, and "Settlements and other" is the sum of the settlements and other land categories. *"Agricultural soils" is the sum of three EPA inventory categories: agricultural soils, liming and urea application.

largely through the mouth, from the animal into the atmosphere.

The amount of CH_4 generated during enteric fermentation is driven by both the characteristics of the animal, in terms of size, growth rate and milk production, and the feed consumed. The quality of feed is primarily controlled by nutritional value and digestibility and can directly affect the efficiency of rumination and the production of CH_4 (Henderson *et al*., 2015). In general, the consumption of readily digestible and nutritious forage can reduce the overall production of CH_4 by ruminants, as the feed moves more rapidly through the digestive tract, and can also increase the productivity of the animal (Knapp *et al*., 2014). Forage with high digestibility tends to have higher proportions of sugars and organic acids, which are rapidly fermentable, and a lower proportion of fibre.

Enteric CH_4 production can be estimated based on feed quality and rate of feed intake (Goopy *et al*., 2016). Diet quality can be inferred by an analysis of representative feed and forage samples. Feed intake, however, is more difficult to quantify. If not measured directly, feed intake can be estimated based on the energy requirement of the animal, which varies significantly depending on species, age and livestock production system. However, the modelling approaches used to estimate enteric fermentation emissions, at Tier 1 and Tier 2,[4] do not fully take into account the impact of feed quality and diet on CH_4 emissions (Vibart *et al*., 2021). This also poses specific challenges when attempting to quantify the impact of dietary additives on CH_4 emissions. Semi-natural forage with a high proportion of plant species secondary metabolites known to inhibit CH_4 production, such as tannins/polyphenols, can have a relatively high fibre content and lower digestibility (Ku-Vera *et al*., 2020; Piluzza *et al*., 2014). This further illustrates the complex relationship between enteric fermentation, forage quality and CH_4 production.

The calculation of CH_4 emissions from enteric fermentation for cattle in Ireland uses a Tier 2 approach based on the methodology outlined by O'Mara (2006) and further updated by O'Brian and Shalloo (2021). First, using livestock numbers from the CSO, the total number of cattle is sub-classified into 11 principal animal classifications based on production type (dairy or beef cattle), sex and age group. Substantial further subdivision is incorporated to account for rearing and finishing systems in both dairy and beef production and three regions: (1) south and east, (2) west and midlands, and (3) north-west (EPA, 2022a).

In general, there is a strong relationship between estimated CH_4 emissions from enteric fermentation and trends in ruminant livestock numbers. This is because livestock numbers are the primary driver of the estimation process, followed by the emission factors assigned to different ruminant categories. Looking at the longer-term trends over the 1990–2020 period, enteric fermentation emissions initially peaked in 1998, at 12,040 kt CO_2 eq yr^{-1} (Figure 2.3). This peak was driven by an increase in total cattle numbers. After 1998 there was a decline in enteric fermentation emissions, which was probably due to a substantial decrease in sheep numbers over the period along with a relatively stable cattle population (Figure 2.3). However, CH_4 emissions have increased substantially since around 2011, reaching a new peak of 12,467 kt CO_2 eq yr^{-1} in 2018.

Increases in total CH_4 emissions from enteric fermentation despite relatively stable total cattle numbers over the last decade are due to an increase in the number of dairy cattle over the same period. For every suckler cow replaced with a dairy cow, there is an increase of approximately 65.9% in enteric CH_4 produced per head. This is based on the emission factors used in the national inventory to estimate enteric fermentation emissions for cattle in 2020, at 122.21 kg CH_4 yr^{-1} per head for a dairy cow and 73.66 kg CH_4 yr^{-1} for a suckler cow (EPA, 2022a). The driver of this difference in emission factors is the higher forage intake per cow for dairy cows than for sucklers, which results in higher CH_4 emissions per head for the former. It should be noted that while emissions efficiency for dairy cows has been improving per kg of milk produced, those improvements are

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[4] The levels at which inventories are reported are referred to as "methodological tiers", which represent degrees of methodological complexity. Tier 1: basic method using relatively simple methodology based on default values. Tier 2: intermediate-level method similar to Tier 1 but with country-specific emission factors and other data included. Tier 3: more complex approaches, possibly using models. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate on condition that adequate data are available to develop, evaluate and apply a higher tier method (IPCC, 2019a).

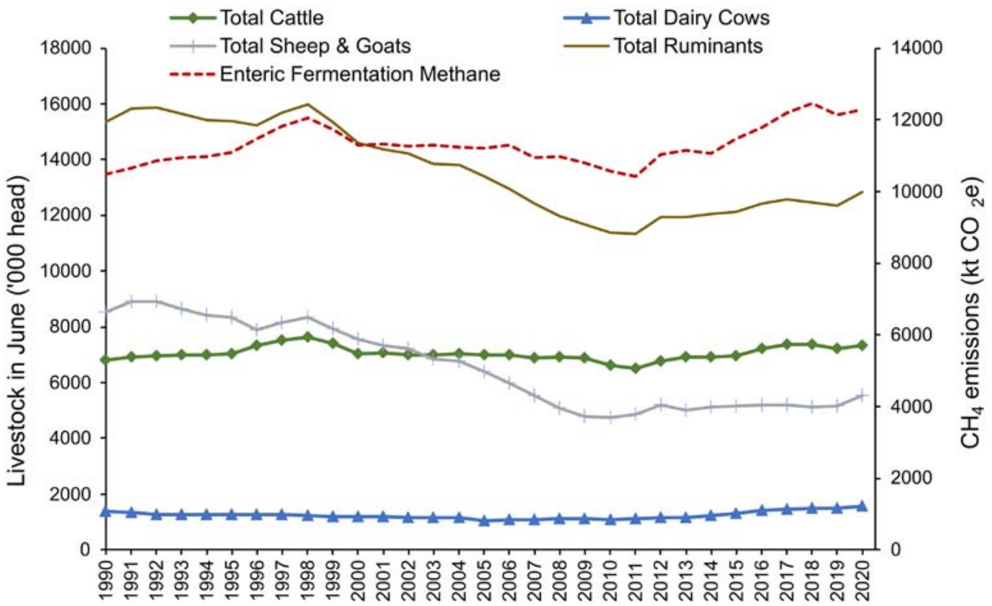

Figure 2.3. Ruminant livestock numbers in Ireland in '000 head in June of each year from 1990 to 2020, broken down into total cattle, total dairy cows and total sheep and goats (data source: CSO (2022)). Enteric fermentation CH_4 emissions for 1990–2020 in kt CO_2 eq yr^{-1} are also shown (data source: EPA (2022a)). Note that CH_4 emissions are plotted on the right-hand *y*-axis and are calculated using EPA animal statistics and not the CSO livestock data that are shown here.

currently being outstripped by increases in the total number of dairy cattle.

There are indications that the relationship between feed intake and CH_4 emissions could be decoupled through a combination of enhanced animal breeding and the use of feed additives that inhibit the production of CH_4 (Mbow *et al*., 2019). The latest research on the mitigation potential of including compounds that act as methanogenic inhibitors in animal feed, such as those derived from macroalgae or seaweed, indicates significant promise (IPCC, 2022b). However, there remain considerable concerns regarding toxicity, palatability and the environmental impacts of large-scale supply chain development required to roll out these measures (IPCC, 2022b). The EU has already approved the use of a feed additive (based on 3-NOP metabolites) for CH_4 reduction in dairy production, which represents a significant advance (Bampidis *et al*., 2021). However, some uncertainty remains regarding the suitability of this additive for use in other ruminant livestock systems (Bampidis *et al*., 2021). The effective implementation of feed additive strategies for CH_4 reduction is particularly challenging in pasture-based dairy systems compared with indoor systems, where there is more direct control of animal diets. However, for pasture-based ruminant livestock there is potential to target dietary supplements at concentrated feed (i.e. feed additives) and water intake (i.e. lipids). Boland *et al*. (2020) found that predominantly pasture-fed dairy cattle given concentrated feed containing C_{18} fatty acids emitted less CH_4 per kg of milk solids produced. In that study, dairy cows fed linseed oil emitted 18% less CH_4 per kg of milk solids produced than cows fed stearic acid or soy oil (Boland *et al*., 2020).

2.3 Agricultural Soil Management

Emissions from agricultural soil management are directly related to the agricultural activities taking place on a given area of land, including the spreading of organic and inorganic fertilisers and excreta deposited at grazing. Between 2016 and 2020, agricultural soil emissions in Ireland were the third largest source from the AFOLU sector, with an average of 6255 (±238) kt CO_2 eq yr^{-1} (Figure 2.2). Looking at the 1990–2020 period, the total emissions from agricultural soils peaked in 1999 at 6997 kt CO_2; following this, they declined to a low of 5438 kt CO_2 in 2011, but they have since increased again to levels similar to those in the late 1990s (EPA, 2022a). The increase in N_2O emissions from agricultural soils since 2011 has been driven by the intensification of production systems, which have seen higher levels of nutrient inputs to soils mainly as a result of dairy expansion. The agricultural soils emissions data, as shown in Figure 2.2, are the sum of three EPA inventory categories: agricultural soils, liming and urea application. Of these three categories, all of which are related to soil management, on average between 2016 and 2020 agricultural soils accounted for 92.3%, with liming at 6.3% and urea application at 1.4%.

Among emissions from agricultural soil management, N_2O is the primary GHG emitted, followed by CH_4 and a relatively small quantity of CO_2 (EPA, 2022a). Direct N_2O emissions from soil management are caused by inputs of nitrogen to grassland and cropland as well as mineralisation processes[5] occurring in these managed soils. In this direct case the N_2O is lost from the soil to which nutrients are applied. In terms of GHG inventory reporting, where possible Ireland applies country-specific emission factors and Tier 1 methodologies based on the 2006 IPCC guidelines for direct N_2O emissions from managed soils (EPA, 2022a). Factors used to estimate direct soil N_2O emissions include inorganic nitrogen fertiliser applied, organic material applied (including slurry and biosolids), mineralisation rates in mineral soils, direct urine and manure inputs from grazing livestock, and the area of organic soils under agricultural management (EPA, 2022a). Emissions from inorganic fertilisers are estimated using a country-specific (Tier 2) approach for the three main inorganic nitrogen fertiliser types available in Ireland: calcium ammonium nitrate, urea, and urea with denitrification inhibitor (Harty *et al*., 2016; Roche *et al*., 2016). Emissions for direct urine and manure inputs by grazing livestock are also calculated using a country-specific emission factor, which is lower than the 2006 IPCC default value (EPA, 2022a; Krol *et al*., 2016).

Indirect N_2O emissions from soil management occur following deposition of nitrogen to soils and waters to which the nutrients have not been directly applied, following leaching and runoff of nitrogen from managed soils. The vast majority of this nitrogen is volatilised from fertiliser and manure in the form of ammonia (NH_3), which is recognised as a major global pathway for nitrogen loss from agricultural systems (Pan *et al*., 2016). Following the deposition of NH_3, indirect emissions of N_2O occur as part of soil microbial processes. Although indirect emissions of N_2O from agricultural soils account for a small proportion of total soil emissions, they are still a significant source. The CO_2 emissions in this category are from liming and urea applications and the associated mineralisation that occurs in soils following these applications.

2.4 Manure Management

Emissions from manure management encompass emissions resulting from the storage and treatment of livestock manure as well as manure deposited directly on grassland by livestock. In the latter instance, manure is taken to include both dung and urine. Between 2016 and 2020, manure management emissions in Ireland were a significant source from the AFOLU sector, with an annual average of 2190 (±49) $\mathrm{kt\,CO_2\,eq\,yr^{-1}}$ (Figure 2.2). Emissions from this category are in the form of both CH_4 and N_2O, with the majority as CH_4. Although most CH_4 emissions are due to enteric fermentation, when looking at the AFOLU sector as a whole, emissions from manure management are still significant. The main factors affecting emissions from manure management are the amount of manure produced and the level of anaerobic decomposition of that manure that occurs. Anaerobic decomposition occurs when manure is stored in slurry tanks or pits, and it can be a significant source of CH_4. Therefore, emissions in this category are linked closely to livestock numbers, the primary contributors among which are cattle, and the manure storage methods used. While the main source of N_2O emissions from the AFOLU sector is agricultural soils, direct and indirect N_2O emissions also occur during the storage and treatment of livestock manure before it is applied to soils. Direct N_2O emissions in this category occur as a result of nitrification and denitrification taking place in the manure, while indirect emissions relate to the deposition of ammonia and other reactive oxides of nitrogen/nitrogen oxide (NOx) following volatilisation.

There was a 17.6% increase in emissions from the manure management category between 2011 and 2020 (EPA, 2022a). In general, more intensive livestock operations are associated with higher stocking densities and therefore more manure

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[5] Soil nitrogen mineralisation is the conversion of organic into inorganic nitrogen and is driven by soil microbial activity interacting with soil physiochemical conditions, nutrient inputs and climatic conditions (Risch *et al*., 2019).

produced per unit of land as well as greater slurry storage requirements. This means that the increase in the dairy sector in Ireland, which is on average more intensive than beef or sheep farming per unit area of land (Haughey, 2021), correlates with the increase in emissions from this category.

2.5 Grassland

The grassland category was a significant contributor to emissions from the AFOLU sector over the 2016–2020 period, at 6968 (±51) kt CO_2 eq yr^{-1} (Figure 2.2). As reflected in the small variation over that period, estimated grassland emissions have been relatively stable since 1990 (EPA, 2022a). As a land use category, grassland encompasses improved grasslands, unimproved grasslands and grassland areas that are not currently in use (for livestock grazing). It is noteworthy that hedgerows are regarded as part of the grassland land use category because they are integral to the grassland landscape, but owing to a lack of data it is not yet possible to include them as GHG flux or carbon stock in this land use (EPA, 2022a). There are strong differences in mean topsoil organic matter content across the country, with higher organic matter strongly associated with soil type and in particular the occurrence of organic soils (Figure 2.4).

In terms of the balance of sinks and sources in the grassland category there are two main divisions:
(1) grassland occurring on mineral soils and
(2) grassland occurring on organic soil that has been converted from peatland. Although grassland occurring on mineral soils is capable of carbon sequestration, grassland occurring on drained and reclaimed peatland is a significant source of emissions, rendering this category the second largest GHG source from the AFOLU sector overall (Table 2.1).

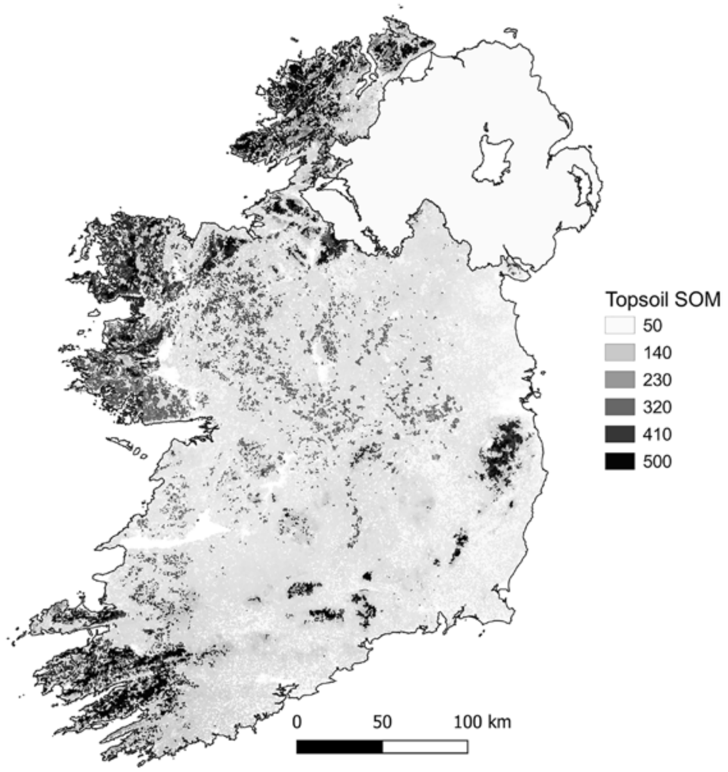

Figure 2.4. Predicted topsoil SOM (SOC content in g C kg^{-1}) in Ireland. The map is based on the dataset Topsoil Soil Organic Carbon (0–20 cm depth) in the EU-25 from de Brogniez *et al*. (2015). The map shows the predicted topsoil organic carbon content, which was produced by fitting a generalised additive model between organic carbon measurements from the LUCAS survey and a set of selected environmental covariates (see de Brogniez *et al*. (2015) for a detailed explanation of the method used for model predictions and the associated standard error).

Table 2.1. Estimated grassland area and soil carbon flux for mineral and organic soils in Ireland in 2020

	Area (kha)	Area share of total (%)	Net carbon stock change (kt C)	Net CO_2 emissions/removals (kt CO_2)
Mineral soils	3874.3	91.9	–625.2	–2291.0
Organic soils	339.4	8.1	2301.1	8432.1
Total grassland	4213.7	–	1675.9	6141.2

Data source: EPA (2022a), plus authors' own calculations. A negative value indicates a carbon sink and a positive value indicates a carbon source.

2.5.1 Soil carbon sequestration and greenhouse gas fluxes from grassland on mineral soils

Grassland occurring on mineral soils accounts for most of the total grassland area; this was estimated to be 91.9% in 2020. In Ireland, estimates of carbon fluxes from grassland on mineral soils in 2020 indicated that this provides a sink of approximately –2291 kt CO_2 (Table 2.1). On a per-hectare basis, this estimate (at Tier 1 level under international reporting standards) is derived from an emission factor of –0.161 t C ha^{-1} yr^{-1} (EPA, 2022a), although that sink is focused on the grassland soils that have been "improved" within the past 20 years and is captured as a land use change effect. This is distinct from an ongoing small sink across all grassland soils, which has implications for future projections because of limits to the level of possible land use change to "improved" grassland.

Increasing carbon storage in mineral soils used for agriculture is estimated to have significant global potential for climate mitigation (Soussana *et al*., 2019). Furthermore, increases in the carbon content of agricultural soils are expected to have a positive impact on soil health and be able to support sustainable land management (Olsson *et al*., 2019). However, the rate at which carbon is sequestered in soils is subject to complex interactions among a range of factors, including climatic conditions, net primary productivity, land management, livestock stocking rates, the intensity of nutrient inputs and soil-specific characteristics. In Ireland, mineral soils under grassland have been estimated to contain carbon stocks of between 3.2% and 6.3% soil organic carbon (SOC) (Kiely *et al*., 2009). This is higher than the average for Europe, where 45% of the mineral soils are estimated to have very low carbon content in the range of 0–2% (Louwagie *et al*., 2009). The higher soil carbon content in grassland soils in Ireland is likely to be due to the high rainfall and the relatively poor drainage of many grassland areas (Xu *et al*., 2011).

It is also important to note that, because of data constraints, current GHG inventory reporting does not capture the differences between levels of management, aside from the broad classification of improved and unimproved grassland. Therefore, it can be expected that actual carbon fluxes vary considerably across grasslands in Ireland. Ongoing fluxes for grasslands on mineral soils have been estimated to range from net sources of 0.4 t C ha^{-1} yr^{-1} to net sinks of 1.0 t C ha^{-1} yr^{-1} (Lanigan *et al*., 2018).

Globally, the soils with the greatest potential to respond to measures targeted at increasing soil organic matter content are those that are currently low in carbon and in a degraded state. Grassland soils that currently contain large stocks of carbon do not necessarily have the largest potential for further carbon sequestration. This is because carbon sequestration in mineral soils approaches a state of equilibrium around 30–70 years after the last disturbance event (Klumpp and Fornara, 2018). This temporal relationship has also been observed in long-term agricultural field trials in cropland (Poulton *et al*., 2018). The potential to reach a state of soil carbon equilibrium represents a significant limitation when considering the long-term sequestration potential of grassland soils. Separately, from a scientific perspective, another challenge is the technical difficultly associated with measuring on-farm rates of carbon sequestration on an annual scale. As the majority of grassland soils in Ireland already contain a large stock of carbon, quantification of the relatively small amount of additional carbon sequestrated annually is very difficult (Byrne *et al*., 2018). We note that efforts are under way to improve the level of data, in terms of quality and resolution, available regarding soil carbon and terrestrial GHG fluxes in Ireland (see section 6.3.7).

2.5.2 Soil carbon sequestration and greenhouse gas fluxes from grassland on organic soils

Grassland occurring on organic soils accounts for a relatively small portion of the total grassland area in Ireland, estimated at 8.1% in 2020. However, despite this small area these grasslands and their soils contribute to significant carbon losses, which outweigh considerably carbon sequestration occurring on grasslands on mineral soils (Table 2.1). Estimates of carbon fluxes from grassland on organic soils in 2020 indicated that these were a source of approximately 8432.1 kt CO_2 (Table 2.1). On a per-hectare basis, this estimate (at the Tier 1 level under international reporting standards) is derived from an emission factor of 6.78 t C ha^{-1} yr^{-1} (EPA, 2022a).

The area of organic soil under agricultural management in Ireland was estimated to be up to 339,400 ha in 2020 (EPA, 2022a). However, there is a relatively high degree of uncertainty associated with this land in terms of its spatial extent and the hydrological characteristics of organic soils under agriculture. The vast majority of this land is used as grassland, with only a very small proportion used as cropland (Donlan and Byrne, 2015). Organic soils under grassland management are used for livestock grazing as well as for hay and silage production, with various levels of historical anthropogenic intervention having taken place to make the land more suitable for forage growth and animal trafficability. Carbon fluxes associated with these organic soils are complex and depend on the biogeochemical characteristics of the soil, historical and current management, and climate (Renou-Wilson, 2018). Site studies have shown that the nutrient status of these organic soils also influences their carbon storage dynamics (Renou-Wilson *et al.*, 2015).

2.6 Wetland

The wetland category was a significant source of GHG emissions over the 2016–2020 period, estimated at 2971 (± 539) kt CO_2 eq yr^{-1} (Figure 2.2). In Ireland, for the purpose of GHG inventories, wetland is categorised as either unmanaged or managed. Managed wetlands comprise peatlands that have been drained for the purpose of commercial harvesting of peat for energy generation and horticultural use, while unmanaged wetlands include peatlands not commercially exploited, inland marshes, salt marshes, moors and heathland, and intertidal flats.

Over the 1990–2020 inventory reporting period, the wetland category remained a significant and consistent source of emissions, albeit with relatively large interannual variation (EPA, 2022a). The key driver of these emissions is the spatial extent of peatland drainage. As water tables are lowered, CO_2 emissions increase through the oxidation of organic matter, and CH_4 emissions from the drained surface tend to decrease. However, hot-spots of CH_4 emissions can occur in areas of standing water such as drains, and increased N_2O emissions have been observed where nutrient-rich organic soils are drained (Wilson *et al.*, 2016). It is noteworthy that, although peatland cover is estimated at only 14.48% (Figure 1.4), this area is estimated to account for 75% of the total soil carbon stored in Ireland (Byrne *et al.*, 2018). Therefore, the status of peatlands as a net source of emissions is of particularly significant concern to the overall status of the AFOLU sector's GHG balance.

2.6.1 Methane emissions from wetland

The production of CH_4 from soils occurs as a result of the action of methanogenic microbes that are active under anoxic soil conditions (Kotsyurbenko *et al.*, 2019). Under oxygenated soil conditions, organic matter is broken down relatively rapidly as part of the remineralisation process, resulting in the release of CO_2, which generally limits the accumulation of SOC. When soil conditions become anoxic, as under waterlogged conditions, the development of a methanogenic microbial community leads to the dominance of anaerobic respiration in the breakdown of organic matter with associated CH_4 production (Kotsyurbenko *et al.*, 2019). The dominance of anaerobic respiration can lead to the long-term accumulation of SOC whereby carbon inputs from photosynthesis are greater than the rate of soil respiration. Therefore, the dominance of anaerobic respiration in peatlands, as in the case of intact peatlands in Ireland, is associated with a reduction in CO_2 emissions, an increase in CH_4 emissions and long-term accumulation of carbon stocks (Byrne *et al.*, 2018).

Drained peatlands are generally considered to be insignificant CH_4 sources due to the dominance of aerobic respiration processes. Yet this can change depending on seasonality in water table levels, whereby rewetting can temporarily convert drained peatlands to CH_4 sources (Sirin *et al.*, 2012). Importantly, the drainage systems used to maintain peatlands and organic soils for extraction or cultivation are themselves potential sources of CH_4. Although such drainage ditches may occupy a small areal proportion of the landscape, they can still be significant sources of CH_4 emissions (Sirin *et al.*, 2012).

2.7 Settlements and Other Land

The settlements and other land categories accounted for an estimated GHG source of 236 (±33) kt CO_2 eq yr^{-1} over the 2016–2020 period (Figure 2.2). Of these emissions, settlements accounted for 78.1% and other land accounted for the remaining 21.9%. The estimated emissions for the settlement category are primarily driven by the conversion of land from other categories to settlement through the process of development. As has been noted, a significant increase in the area of settlement in Ireland occurred during the 1990s and early 2000s (Figure 1.2), which was closely linked to economic conditions at that time. The level of change in settlement land area has since plateaued, but change is still ongoing, albeit at a lower rate. Over the 1990–2020 period, estimated emissions for settlements peaked in 2007 at 597 kt CO_2 eq, an increase of 589%, which was due to the large increase in development activity. The emissions decreased from that point to current levels, which are less than half those in 2007 but are once again rising.

In inventory calculations, it is assumed that all biomass is removed during conversion to settlement, which results in immediate carbon loss (EPA, 2022a). Note that this does not include potential biomass restoration that may occur following developments such as the creation of parks or garden areas. For soils it is assumed that 50% of soil carbon is lost on conversion to settlement, but this value comes with a high level of uncertainty (EPA, 2022a). The conversion from forestry to settlement is dealt with separately since there is more information available with which to make estimates.

Land that remains in the other land category, which includes all lands not classified as grassland, wetland, cropland, forestry or settlement, is assumed to be in a state of equilibrium for carbon stored in biomass, soils and other pools (e.g. leaf litter). Therefore, only changes of other land to or from another category have an impact on the emissions for this category. The other land category is essentially calculated as a "residual" area from the rest of the land use categories, and it can be expected that a relatively high level of uncertainty is associated with its GHG estimates. Without a high-resolution land use map, it is difficult to make any major advances in how these estimates are calculated (but see section 6.3.1).

2.8 Cropland

Cropland was a minor net sink over the 2016–2020 period estimated at –131 (±41) kt CO_2 eq yr^{-1} (Figure 2.2). The role of cropland soils as a carbon sink is significant, but it is also important to note that this does not account for emissions related to nutrient inputs in croplands that are captured under agricultural soil management. Driving this net sink are complex interactions in land use change transitions between cropland, with temporary grassland phases in crop rotations playing an important role. Cropland soils generally act as a net carbon sink during the temporary grassland phase, with carbon lost during the crop cultivation phase (Byrne *et al.*, 2018). However, without a temporary grassland phase the outcome is quite different. Where spring barley has been continuously cultivated using conventional tillage methods in Ireland, the soil has been observed to be a net source of around 1 t C ha^{-1} yr^{-1} (Ceschia *et al.*, 2010). This highlights the important role that management plays in the GHG flux status of cropland. Specifically, the frequency and duration of the grassland phase of a crop rotation cycle affect the overall carbon balance of these soils.

Croplands generally store less carbon than grassland soils due to their greater level of disturbance during the cultivation process, which leads to enhanced rates of mineralisation and subsequent CO_2 release. Nevertheless, the amount of carbon stored in cropland soils globally has been estimated at more than 140 Pg C in the top 30 cm of cropland soil, which represents around 10% of the total global SOC pool (Zomer *et al.*, 2017). Even more than grasslands, land used for crop production is vulnerable to unsustainable management, which can result in carbon loss as well as other processes of land degradation (Olsson *et al.*, 2019). Globally, compared with carbon content prior to their cultivation it is estimated that croplands have lost between 20% and 60% of their organic carbon, and they continue to be a net source of carbon under conventional agricultural practices (Olsson *et al.*, 2019).

At a global scale, enhancing the amount of carbon sequestered in cropland soils is recognised as having the capacity to significantly contribute to climate change mitigation (Smith *et al.*, 2019). Increasing soil carbon in these areas also has significant co-benefits for other soil properties such as nutrient and water retention. However, the current carbon stock in cropland soils varies significantly across the globe. The majority of carbon stored in cropland soils is located across northern latitudes, while large parts of the cropland areas across India, the Sahel and Australia have relatively low levels of carbon (Zomer *et al.*, 2017). Cropland soils that have a higher standing carbon stock may be closer to equilibrium or saturation levels than soils that currently have a lower carbon content (see section 2.5.1). However, this represents an opportunity for cropland soils that have a lower carbon content and therefore significant scope for increasing sequestration under appropriate management (Paustian *et al.*, 2019).

2.9 Forestry and Harvested Wood Products

The combined forestry land and HWP categories were a major next sink over the 2016–2020 period, estimated at –2957 (±338) kt CO_2 eq yr^{-1} (Figure 2.2). Annual carbon removals decreased over the period 1990–1999. However, annual CO_2 removals by forest land use have increased since the year 2000. This is strongly linked to harvesting cycles. When assessing the forestry sector in terms of its carbon stocks, and ongoing GHG fluxes, there are three main components: (1) forest biomass, comprising above- and below-ground biomass and litter, (2) forest soils and (3) HWPs. The approach to forestry in the national GHG inventory is based on gains and losses using Tier 3 methodologies. Carbon pool reporting is calculated via a modelling approach using the Canadian Forest Service Carbon Budget Model Framework (Kurz *et al.*, 2009). This model uses activity data from the forestry sector to report biomass carbon stock changes. Changes in the forest land area as well as information on the age structure, species and productivity index of the forest stock are key inputs to the model and are derived from a range of sources (EPA, 2022a).

2.9.1 Carbon stocks in forest land

The National Forest Inventory (NFI) of Ireland is a comprehensive and repeated survey of permanent forest land (DAFM, 2021c). Plots are selected using a grid (2 km × 2 km) that can achieve a representative sample of national forest land. The plot selection process resulted in 17,423 sample points, each of which was 25.24 m in diameter and marked permanently to allow resampling on the same plot. The latest NFI survey estimated that the forest estate, including carbon in above- and below-ground biomass, litter and soils, was a reservoir of 311.7 million tonnes of carbon (t C) (Table 2.2).

The vast majority of the 311.7 million t C stored in forest land is in the soil pool, making up 79.1% of the total (Table 2.2). The two other main carbon stock pools in the system are above- and below-ground biomass, which made up 14.1% and 3.3% of carbon in 2017. Reflecting the increase in forest area and the growth of existing forest stands, the amount of carbon stored in above-ground biomass increased from 30.6 million t C in 2006 to 45.6 million t C in 2017. Over the same period, NFI data indicated a decrease in the stock of carbon in forest soils (but see footnote b of Table 2.2). There are complex dynamics at play between carbon stored in biomass and GHG fluxes from forest soils.

There are also key differences between natural and managed forests in the way they partition carbon between biomass and soils. Although the primary productivity of natural and managed commercial forests is similar, managed forests tend to allocate more biomass to above-ground carbon pools than unmanaged forests (Noormets *et al.*, 2015). This has implications for the long-term carbon sequestration potential of managed forests in Ireland, which are by far the dominant type of forest land.

2.9.2 Harvested wood products

In 2021, roundwood harvesting in Ireland was at its highest level since records began, at 4.33 million m^3 (DAFM, 2022a). Roundwood supply forms the basis of several production streams. In 2019, 34% of the

Table 2.2. NFI carbon stocks for the forest estate in Ireland in 2006, 2012 and 2017[a]

Carbon stock	2006 (Mt CO_2)	2012 (Mt CO_2)	2017 (Mt CO_2)[b]
Above-ground biomass	30.6	39.7	45.6
Below-ground biomass	6.7	8.8	10.3
Deadwood	1.2	2.5	2.1
Litter	2.3	6.3	7.1
Soil	304.9	323.7	246.6
Total	**345.7**	**381.0**	**311.7**

[a]Carbon is given in millions of tonnes of CO_2, where above-ground biomass includes all living stems, branches and needles/leaves based on a stump height at 1% of total tree height, below-ground biomass includes all roots to a minimum diameter of 5 mm, and deadwood includes all logs, stumps and branches with a minimum diameter of 7 cm.

[b]Due to methodological improvements, carbon stock estimates from the 2017 NFI are not directly comparable with 2006 and 2012 data. These methodological improvements include more accurate biomass equations, new classification systems and associated stock values for soil and deadwood. See DAFM (2018b) for details on field procedures and methodology.

Source: Adapted from DAFM (2018c).

supply of roundwood in Ireland was used for energy generation, 33% was used for construction and panel board production, 21% was used for packaging, fencing and posts, and the remaining 12% was for other use and residues (Figure 2.5). Of the timber used for energy generation, 62% was used by timber processors in internal processing activities and the remaining 38% was used for external energy generation (COFORD, 2022).

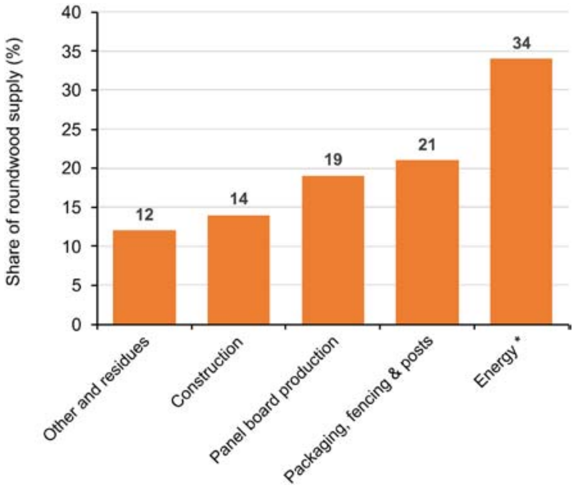

Figure 2.5. Use of harvested timber (roundwood supply) in Ireland in 2019. Data source: COFORD (2022). *Energy includes the energy used in timber processing as well as that used for external energy generation, which includes combined heat and power generation and commercial and residential use of woodfuel.

The way in which harvested roundwood supplies are used has important implications for the carbon sequestration potential of the HWP category. IPCC inventory guidelines on the calculation of carbon storage in harvested wood are based on product type and the expected life cycle of products (IPCC, 2006). Therefore, the proportion of harvested wood used for long-lived products, such as construction materials, compared with the proportion used to produce short-lived products, such as paper, or used as fuel or energy feedstock affects the net carbon balance of the forestry sector (Matthews *et al*., 2015; Olsson *et al*., 2019). In 2019, construction and panel board production made up 33% of roundwood supply usage in Ireland (Figure 2.5), which has the potential to provide a much longer carbon store than timber used for energy generation. Another factor to consider when assessing the effect of HWP usage is the potential impact on GHG emission displacement or avoided emissions. A reduction in the use of an emission-intensive material such as concrete in building construction through the increased use of timber can contribute to climate change mitigation (Kurz *et al*., 2016).

2.9.3 Emissions from forest land soils

The characteristics of the soil on which afforestation occurs have important consequences for soil carbon. Generally, where afforestation takes places on organic soils, this is associated with a reduction in soil moisture due to both initial draining of the land for planting and subsequent changes in bog vegetation and evapotranspiration rates. Such a reduction in moisture is likely to lead to a significant loss of organic carbon stocks due to mineralisation processes. Globally, afforestation on peatlands across temperate regions has resulted in estimated carbon losses of between 0.9 and 9.5 $\mathrm{t\,CO_2\,ha^{-1}\,yr^{-1}}$ (Olsson *et al.*, 2019). In Ireland, the afforestation of Sitka spruce on organic soils has also been shown to be a significant source of soil carbon emissions (Lane, 2016). Afforestation on mineral soils can result in an increase in soil carbon stocks or a loss of carbon. The relationship is not straightforward and depends on the initial soil characteristics, impact of land preparation and forestry management. Despite an initial loss of carbon associated with site preparation, the afforestation of Sitka spruce on wet-mineral gley soils has been shown to be a significant soil carbon sink in central Ireland, at a rate of 1.83 $\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$ over a 47-year period (Reidy and Bolger, 2013). However, there is uncertainty regarding the impact of afforestation on the soil carbon balance for a range of wet mineral soils with higher organic matter content, such as peaty podzolic soils.

There is strong evidence to suggest that the drainage of peatlands and subsequent afforestation with conifer species in maritime temperate regions such as Ireland results in these soils acting as net carbon sources (Jovani-Sancho *et al.*, 2021). Since there has been significant afforestation on peatland soils in Ireland, particularly up to and including the 1990s, this has had an impact on the overall carbon sequestration potential of forestry nationally. This impact can be seen when considering the carbon stock changes in the GHG inventory category "forest remaining forest land". In 2020 there was an estimated 270,360 hectares of forest remaining forest land on organic soils and 445,990 hectares on mineral soils in Ireland (EPA, 2022a). Among these, the organic soils were estimated to be a carbon source of 431.24 kt C and the mineral soils a source of 9.16 kt C (EPA, 2022a). It is important to consider this along with the net carbon flux for forestry, which was –520.43 $\mathrm{kt\,CO_2}$ in 2020, driven by the stock change of carbon storage in biomass. Clearly, if all forestry were on mineral soils, it is likely that there would be significantly less carbon loss from soils over time, and the overall sink provided by forestry would be enhanced substantially.

Information Box 2.1. Methane emissions and metrics

By 2020, the concentration of methane (CH_4) in the atmosphere had increased by 262% since pre-industrial times (WMO, 2021), and this trend shows no sign of slowing down (Jia *et al*., 2019). Globally, over half of CH_4 emissions come from food production (Saunois *et al*., 2019), and CH_4 emissions from agriculture continue to increase (Figure 2.6) in line with increases in ruminant livestock numbers and rice cultivation (Arneth *et al*., 2019).

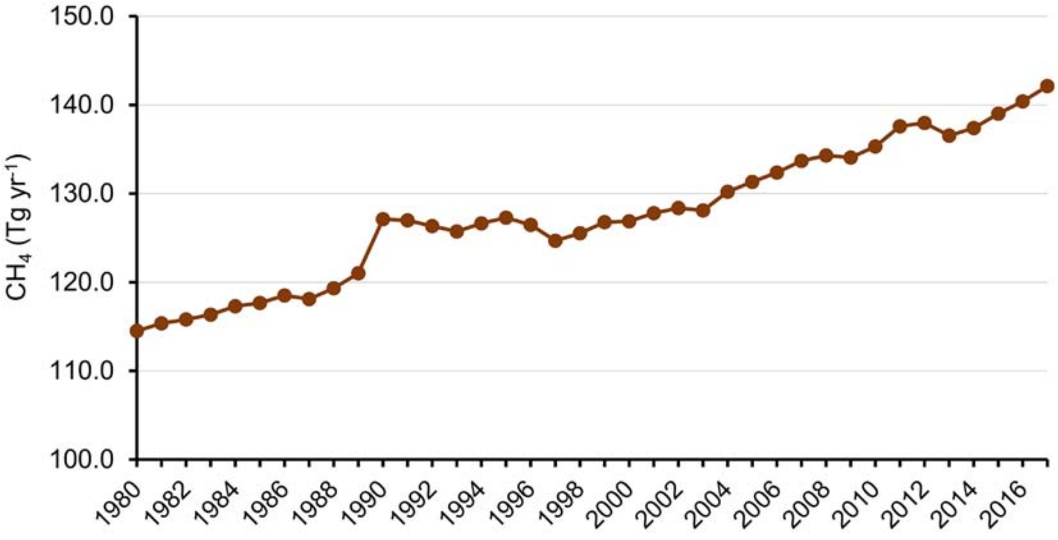

Figure 2.6. Global CH_4 emissions from agriculture for the period 1980–2017. Data source: FAOSTAT (2020).

Methane is a considerably more powerful gas than CO_2 in terms of radiative forcing effect per molecule, and each kg of CH_4 emitted has a global warming potential effect over 100 years (GWP_{100}) 28 times greater than that of each kg of CO_2 emitted. In 2020, CH_4 was estimated to have contributed 16% of total radiative forcing since pre-industrial times, second only to CO_2 (WMO, 2021). However, CH_4 breaks down in the atmosphere much more rapidly than CO_2 and nitrous oxide (N_2O). Analysis from the Global Methane Budget for the 2000–2017 period indicates that CH_4 remains stable in the atmosphere for approximately 9.6 years (Saunois *et al*., 2019). Consequently, it acts as a “short-lived climate pollutant” (SLCP), with its climate-forcing effect being more closely related to flows than to the cumulative impact of long-lived “stock” pollutants such as CO_2 and N_2O (Allen *et al*., 2018). This means that, unlike those CO_2 and N_2O emissions, CH_4 emissions do not need to reach (net) zero to stabilise the climate. However, global climate modelling indicates that global CH_4 reductions of 35% or more by 2050, relative to 2010, would be required to achieve climate stabilisation at a global mean surface temperature of 1.5°C above pre-industrial times with no or limited overshoot (IPCC, 2018).

A GWP* aggregation metric has been proposed to better represent cumulative climate forcing of different emissions through time than GWP_{100} (Allen *et al*., 2018; Cain *et al*., 2019). According to the GWP* method, the future climate forcing effect of emissions depends on the recent *change* in CH_4 emissions (usually over a 20-year period). This representation is more consistent with climate modelling used to determine pathways towards climate stabilisation at the global scale to 2050 (IPCC, 2018) and could be used to determine the contribution of national CH_4 emissions more accurately, at given fluxes of CO_2 and N_2O, to climate neutrality. However, while GWP* is well aligned with climate forcing at the global scale, it involves the “grandparenting” of past CH_4 emissions, with pronounced implications for how the global CH_4 budget is apportioned, and that may be challenged in terms of international fairness (Rogelj and Schleussner, 2019).

Information Box 2.1. Continued

Furthermore, GWP* is not a useful metric when attribution of warming effects is required to calculate the contribution of specific activities or products to climate change, for example when calculating the "carbon footprints" of countries, sectors or food products (Saget *et al*., 2021).

Thus, while the GWP* metric could be valuable in illustrating climate mitigation scenarios through time where CH_4 emissions have stabilised or are in decline globally (Lynch *et al*., 2020), it is not useful for the national allocation of CH_4 targets or for national reporting to the UNFCCC, which remains based on GWP_{100}. Nonetheless, there are moves towards setting separate targets for CH_4 that recognise the distinct contribution of this important GHG to climate change and the relevance of a non-zero target for its emission (European Commission, 2020b). In the light of this direction of travel, "net-zero" GHG balances for 2050 have been calculated using GWP_{100} with and without the inclusion of CH_4 in this report (see Chapter 4). The latter approach assumes that Ireland's AFOLU sector will comply with separate CH_4 emission targets in line with the Paris Agreement. Such national targets are a long way from being established and may be coordinated at the EU level – but, given the high per-capita CH_4 emissions in Ireland, they could represent a reduction of 30–80% relative to a 2010 baseline (Prudhomme *et al*., 2021).

3 Climate Change Scenarios and Impacts

This chapter provides an overview of changes in global and regional climates and the likely impacts of these on the ecosystem functioning of the terrestrial land system. Section 3.1 explores observed and projected changes in the global and regional climates under different global warming and socioeconomic development pathways. This includes an assessment of the latest IPCC climate change projections for the northern Europe region, which is the finest scale relevant to Ireland in that assessment (IPCC, 2021a). This is followed by an exploration of the results of regional climate model (RCM) analyses for climate change in Ireland. Section 3.2 outlines a systematic review analysis that was conducted to investigate the impacts of climate change on the functioning of the land system in Ireland.

3.1 Regional and National Climate Change Projections

The latest findings from Working Group I of the IPCC indicate that the global climate system has already changed significantly, affecting every inhabited region of the globe (IPCC, 2021b). Changes to the climate system are occurring at an unprecedented rate, and it is now unequivocal that these changes are being caused by anthropogenic activities (IPCC, 2021b). The likely range of human-caused global surface temperature increase between 1850–1900 and 2010–2019 is 0.8°C, and each of the last four decades has been warmer than any preceding decade going back to 1850.

Atmospheric concentrations of CO_2 are at their highest in at least 2 million years (IPCC, 2021b), and in 2020 CO_2 levels were 149% higher than in the pre-industrial period (WMO, 2021). Meanwhile, CH_4 was 262% and N_2O 123% higher than pre-industrial levels in 2020, with increases showing little sign of slowing down (WMO, 2021). The single most important GHG is CO_2, which accounted for approximately 66% of the warming effect on the global climate system in 2020 (WMO, 2021). Although CO_2 emissions are primarily due to fossil fuel combustion and cement production, the natural system plays a hugely important role in carbon cycling. The ocean acts as an important carbon sink, while the land system acts as both a sink and a source of carbon in a complex manner (IPCC, 2019c).

Global warming and precipitation are fundamentally linked; for every 1°C increase in global temperatures, there is approximately a 7% increase in the water-holding capacity of air (Trenberth, 2011). This results in more water vapour in the atmosphere, which alters precipitation patterns and can produce more intense rainfall events and flooding (Trenberth, 2011). Globally, precipitation over land has increased since 1950, with the rate of change increasing in recent decades, and has been accompanied by a poleward shift in storm tracks and altered precipitation patterns and seasonality (IPCC, 2021b).

3.1.1 Global climate change scenarios and projections

To allow for a range of future climate and socioeconomic scenarios to be explored, the latest IPCC assessment reports used five different combinations of representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) (see Information Box 3.1 and IPCC (2021a)). These are described as ‘SSP*X*-*Y*’, where the *X* represents the SSP scenario and *Y* represents the RCP level.

Summary of the SSP-RCP scenarios considered:

- **SSP1–1.9**. Represents a pathway that limits warming to around 1.5°C above pre-industrial levels by 2100 with limited overshoot. Net zero is reached by the middle of the century.
- **SSP1–2.6**. Represents a pathway where the warming level stays below 2°C this century, with net zero reached after 2050.
- **SSP2–4.5**. Represents a pathway where the warming level reaches around 2.7°C above pre-industrial levels by 2100. This is consistent with the upper end of nationally determined contribution emission levels by 2030.
- **SSP3–7.0**. Represents a pathway with a moderate to high warming level reaching 3.6°C above pre-industrial levels by 2100. This scenario is consistent with no additional climate policy and

Information Box 3.1. Representative concentration pathways and shared socioeconomic pathways

Scenarios are essential in climate-related research, as they allow exploration of possible future climates and impacts on human and natural systems, as well as aiding decision-making. In recent decades several stages of scenario development have occurred as climate science itself has further evolved. The latest analysis from the IPCC as part of its Sixth Assessment has moved towards combining RCPs and SSPs. This allows a range of possible climate and socioeconomic futures to be explored together.

RCPs include time series of emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover (Moss *et al*., 2008). The word *representative* signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. Radiative forcing is the change in energy flux in the atmosphere caused by natural or anthropogenic factors and is measured in $\mathrm{W\,m^{-2}}$. Different gases and aerosols have different associated radiative forcings and are usually given in terms of the CO_2 equivalence to allow for comparison between sources. The word *pathway* emphasises the fact that both the trajectory taken over time and the long-term concentration levels of GHGs are important (Moss *et al*., 2010). In the latest assessment from Working Group I of the IPCC, five RCPs are used to explore different pathways and their consequences for overall radiative forcing levels and the climate system more broadly (IPCC, 2021a). These are RCP1.9, RCP2.6, RCP4.5, RCP7.0 and RCP8.5, where the numerical value indicates the approximate level of radiative forcing ($\mathrm{W\,m^{-2}}$).

Different global changes in social and economic development can result in substantially different future emissions of GHGs and therefore have different impacts on global warming levels. The five SSPs were developed to complement the RCPs with varying socioeconomic challenges to adaptation and mitigation (Nakicenovic *et al*., 2014; O'Neill *et al*., 2014). This essentially represents a second phase of emission scenario development, and the SSPs include a range of parameters that can be used to explore alternative development pathways over the rest of the century. These include changes in population and demographics, gross domestic product, the nature of international trade, technological development, the effectiveness of governance and ecological factors (O'Neill *et al*., 2014).

Summary of SSPs:

- **SSP1:** Sustainability focused and high adaptive capacity. Characterised by a peak and then a decline in population, with environmentally positive technological progress and consumption patterns with lower resource use. Pathway results in low challenges for climate mitigation and adaptation.
- **SSP2:** Middle of the road. Characterised by medium population growth with technological progress and consumption patterns following past trends. Pathway results in moderate challenges for climate mitigation and adaptation.
- **SSP3:** Regional rivalry and resource intensive, with low adaptive capacity. Characterised by high population growth, slow rates of technological progress and material-intensive consumption patterns. Pathway results in high challenges for both climate mitigation and adaptation.
- **SSP4:** Inequality with low adaptive capacity. Characterised by medium population growth with moderate action on climate mitigation but with high regional and local inequality. Pathway results in low challenges for climate mitigation with high challenges to adaptation.
- **SSP5:** Fossil-fuelled development with high adaptive capacity. Characterised by a peak then a decline in population but with resource-intensive consumption patterns and lifestyles. Pathway results in high challenges for climate mitigation with low challenges to adaptation.

The combination of SSP-based socioeconomic scenarios and RCP-based climate projections provides an integrative frame for climate impact and policy analysis. The utility of this approach is apparent when examining future scenarios within different sectors. As part of its assessment of global land use change under different SSPs under a global warming scenario of RCP1.9, the IPCC SRCCL found that increasing

Information Box 3.1. Continued

afforestation rates was important across all assessed pathways in which this warming level was feasible. The change in forestry cover was largest under a “sustainability-focused” pathway (SSP1), at 3.4 million km^2 of additional forestry by 2050 and 7.5 million km^2 by 2100, compared with a 2010 baseline (IPCC, 2019d). Levels of increased forestry required under “middle of the road” (SSP2) and “resource-intensive” (SSP5) pathways were also very large but with different associated trade-offs. In terms of land use required, the deployment of bioenergy is expected to rival that of afforestation under assessed SSPs in SRCCL where global warming is limited to levels consistent with RCP1.9 (IPCC, 2019d). Notably, however, bioenergy plays a smaller role in land use towards the end of the century under a “sustainability focused” (SSP1) pathway than under a “resource-intensive” (SSP5) pathway. Such large increases in the levels of global afforestation and land use for bioenergy crops pose major challenges to sustainability. Indeed, where implemented at very large scales there are significant risks to global food security. In this case food security risks primarily arise through increased land competition, while there are also considerable risks to biodiversity, especially where monocultures of bioenergy crops and fast-growing non-native tree species dominate (Smith *et al*., 2019).

particularly high non-CO_2 emissions associated with intensive resource use and consumption patterns.

- **SSP5–8.5**. Represents a pathway with a very high warming level reaching around 4.4°C above pre-industrial levels by 2100, no additional climate policy and CO_2 emissions that are double current levels by 2050.

For both the SSP1–1.9 and SSP1–2.6 pathways, there would need to be significant progress in reducing GHG emissions in the near and medium term. These pathways could be described as the best cases for limiting global warming to levels in line with or close to those outlined in the 2015 Paris Agreement.

In terms of global impacts at different warming levels, there are some global trends but also important regional differences. Three levels of warming relative to pre-industrial levels are used for projections: +1.5°C, +2°C and +4°C.

Summary of observed and expected changes for selected indicators (for details see IPCC (2021a)):

- **Warm or hot extremes** (frequency or intensity): increases have been observed since 1950 and are virtually certain to increase further with all three warming levels.
- **Cold extremes** (frequency or intensity): decreases have been observed since 1950 and are virtually certain to decrease further with all three warming levels.
- **Heavy precipitation events** (frequency, intensity, amounts): increases over land have been observed in most global regions since 1950 and are projected to increase with all three warming levels, with increasing likelihood at +4°C.
- **Agricultural and ecological droughts**[6] (frequency and/or intensity): increases have been observed in some global regions since 1950 and are projected to increase in the future in more regions with all three warming levels, with increasing likelihood at +4°C.
- **Co-occurring droughts and heatwaves** (compound events): the observed frequency has increased since 1950. Under all three warming levels the frequency and intensity of co-occurring droughts and heatwaves are likely to increase.
- **Extreme sea levels** (frequency): the observed frequency has increased since 1960, and it is very likely that the frequency of these events will increase under all three warming levels for the 21st century.

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[6] Agricultural and ecological droughts are defined as “a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general (biome dependent)” (IPCC, 2021a).

3.1.2 Observed and projected climate change in northern Europe

The northern Europe region (of which Ireland is part) is the finest level of regional information available from the latest IPCC global assessment (IPCC, 2021a). The Interactive Atlas[7] was used to extract data for the northern Europe region based on the latest IPCC WGI analysis (Gutiérrez *et al*., 2021). The Interactive Atlas was constructed based on the Coupled Model Intercomparison Project Phase 6 (CMIP6), which is an initiative of the World Climate Research Programme (WCRP, 2022).

Observed changes in the climate system for the northern Europe region (Gutiérrez *et al*., 2021):

- Across all sub-regions of Europe, datasets show consistent observed warming of mean annual temperatures since 1980 of between 0.04°C yr^{-1} and 0.05°C yr^{-1}.
- In northern Europe, mean annual temperatures increased by 0.4°C per decade between 1970 and 2008.
- Precipitation pattern trends in northern Europe show large spatial variability and are subject to decadal variability driven by the North Atlantic Oscillation.
- There is *medium confidence* that annual mean precipitation in northern Europe has increased since the early 20th century.

A selection of climatic variables were extracted to provide an overview of projected changes to climate in the northern Europe region: mean temperature, maximum temperature, frost days, total precipitation, maximum 5-day precipitation and consecutive dry days (the results are summarised in Table 3.1). The projections give the median as well as the 10th and 90th percentiles for each variable for the near-term (2021–2040), medium-term (2041–2060) and long-term (2081–2100) ranges. Four SSP–RCP combined scenarios were considered: SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5 (see Information Box 3.1 for descriptions of SSPs and RCPS). Only annual projections for these variables were considered here; note that there are strong differences in seasonality for some variables not captured at the annual level.

Important regional projected trends in northern Europe (Gutiérrez *et al*., 2021):

- increasing trend in mean surface temperature (*high confidence*);
- increase in extreme heat events (*high confidence*);
- decrease in the number of frost days (*high confidence*);
- increasing trend in mean precipitation (annual; *high confidence*);
- increase in the occurrence of heavy precipitation events and pluvial flooding (*high confidence*);
- increase in severe windstorms (*medium confidence*) but a decrease in average wind speeds (annual);
- unclear direction of change with regard to the frequency or severity of agricultural/ecological droughts (*low confidence in direction of change*);
- increases in relative sea level, coastal flooding and coastal erosion (*high confidence*).

In terms of change across scenarios and timelines, there are clear increases in the scale of change expected when moving from near to long term and from SSP1–2.6 to SSP5–8.5. Over the period 2081–2100, the median projected temperature increases for northern Europe are 2.6°C under SSP1–2.6 and 5.4°C under SSP5–8.5 (Table 3.1). Similarly, an increase in maximum temperatures is projected over the same period, ranging from a median increase of 2.6°C under SSP1–2.6 to 5.4°C under SSP5–8.5.

The strong increasing trend in mean and maximum temperatures leads to a commensurate projected decrease in frost days (defined as days that have a minimum temperature below 0°C). Even under SSP1–2.6 the projected decrease in frost days is large, at –37.8 days over the 2081–2100 period, while the SSP5–8.5 scenario sees a median decrease of –72.8 days over the same period (Table 3.1). This is likely to have significant impacts on seasonality and ecosystem functioning.

Total precipitation is projected to increase (at annual levels) in northern Europe across all scenarios and time periods, with strong seasonal differentiation. Under SSP1–2.6 the median increase in total precipitation is 6% over 2081–2100, while under SSP5–8.5 the increase over the same period

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[7] IPCC WGI Interactive Atlas available at http://interactive-atlas.ipcc.ch/ (accessed 12 February 2023).

Table 3.1. The CMIP6 projections in the near (2021–2040), medium (2041–2060) and long (2081–2100) terms across four SSP–RCP combined scenarios for the northern Europe region

		SSP1–2.6			SSP2–4.5			SSP3–7.0			SSP5–8.5		
Variable	**Term**	**Median**	**P10**	**P90**	**Median**	**P10**	**P90**	**Median**	**P10**	**P90**	**Median**	**P10**	**P90**
Mean temperature	2021–2040	1.9	1.2	3.5	2.3	1.5	3.1	2.2	1.2	3.3	2.3	1.2	3.5
(Change in °C)	2041–2060	2.4	1.4	3.8	2.8	1.7	4.1	3	1.9	4.1	3.3	2	4.6
(32 models)	2081–2100	2.6	1.2	4.1	3.8	2.2	5.2	4.6	3.3	6.4	5.4	3.9	7.5
Max. temperature	2021–2040	1.8	1.1	3.5	2.1	1.4	3.3	2.1	1	3.1	2.1	1.3	3.6
(Change in °C)	2041–2060	2.3	1.3	3.5	2.6	1.6	3.7	2.8	1.8	3.9	3.1	1.8	4.5
(26 models)	2081–2100	2.6	1.5	3.7	3.3	2.2	4.8	4.4	3.3	6.4	5.4	3.6	7.4
Frost days	2021–2040	–28.5	–56	–14.3	–28.9	–50.1	–14.5	–30.1	–48.7	–12.7	–28.8	–56.5	–13.4
(Change in days)	2041–2060	–37.4	–56.1	–19.3	–37.2	–58.2	–21.8	–39.7	–62.7	–27.5	–43.3	–71.6	–25.8
(25 models)	2081–2100	–37.8	–60.2	–30.4	–48.7	–65.9	–35.3	–62.3	–82.6	–51.5	–72.8	–102.6	–55.2
Total precipitation	2021–2040	4.8	2	8.5	5	2.4	9.2	5.8	1.8	9	5.2	2.3	10.5
(Change in %)	2041–2060	6	2.7	10	7.1	2.4	10.8	7.3	2.6	12.2	7.3	4.2	13.6
(31 models)	2081–2100	6	0.7	12.4	8.1	3	15	11	4.9	17.6	13.4	5.9	21.3
Max. 5-day precipitation	2021–2040	7.2	4.7	11.4	7.2	4.3	11.6	6.7	4.4	10.3	8	4.4	10.7
(Change in %)	2041–2060	7.3	4.2	12.6	8.6	5.4	12.5	9	6.5	13.6	9.9	6.6	15.7
(31 models)	2081–2100	9	2.9	14	12.7	6.9	18.9	16.4	10.3	26.4	19.9	12.7	30.9
Consecutive dry days	2021–2040	0.2	–0.5	1	0.1	–0.5	1.1	0.2	–0.8	1.1	0.1	–0.7	1.2
(Change in days)	2041–2060	0.3	–0.7	1.1	0.1	–0.9	1.2	0.5	–0.8	1.4	0.5	–1	1.6
(30 models)	2081–2100	0.4	–0.7	1.3	0.8	–1.1	1.7	1	–0.5	2.8	1.6	–0.4	3.5

Change is relative to the 1850–1900 reference period and values are annual. Outputs are from multiple model comparisons (number of models indicated for each variable). P10 and P90 refer to the 10th and 90th percentiles, respectively, and are provided to give an indication of the variance associated with the projections. Variable definitions: mean temperature, mean near-surface air temperature; max. temperature, mean of daily maximum temperature; frost days, days with a minimum temperature below 0°C; total precipitation, near-surface total precipitation; max. 5-day precipitation, maximum 5-day precipitation amount; consecutive dry days, maximum number of consecutive dry days (with precipitation of <1 mm).

Data source: Gutiérrez *et al*. (2021).

is 13.4%. In absolute terms this percentage change in precipitation is especially significant in areas with already high rainfall levels, such as the western seaboard of Ireland. Maximum 5-day precipitation is a useful measure when examining extreme changes in precipitation patterns. In northern Europe, the maximum 5-day precipitation is expected to increase by 9% under SSP1–2.6 and 19.9% under SSP5–8.5 over the 2081–2100 period (Table 3.1). This severe level of change is likely to impact on many climate-related risks including flooding, landslides and general soil moisture conditions. Alternatively, the number of consecutive dry days can give an indication of drying trends, which can be related to the occurrence of drought events. For northern Europe there are predicted small increases in consecutive dry days of 0.4 days under SSP1–2.6 and 1.6 days under SSP5–8.5 (Table 3.1). This is in line with the general *low confidence* in the change related to agricultural and ecological droughts for this region (Gutiérrez *et al.*, 2021).

For the temperature- and precipitation-related variables explored using the regional-level data, it must be noted that projected changes will also be affected by seasonality. There are also likely to be strong influences of topography, aspect and elevation in terms of local impacts, which would not be captured by the global climate models used for this regional analysis.

3.1.3 Observed and projected climate change for Ireland

Ireland's climate has already been affected by climate change. The EPA Climate Status Report 2020 outlines the observed changes in detail (EPA, 2021a).

Key observed changes to the climate system in Ireland (EPA, 2021a):

- In 2019 GHG measurements at Mace Head, County Galway, were the highest since records began, with concentrations of CO_2 at 50%, CH_4 at 170% and N_2O at 20% higher than pre-industrial levels.
- Mean annual temperature has been increasing at a rate of 0.078°C per decade since 1900 and is now 0.9°C higher than in the early 1900s.
- The period from 2006 to 2015 was the wettest on record, with evidence of an observed trend towards an increase in winter rainfall and a decrease in summer rainfall.
- Soil moisture deficits measured at Dublin Airport in June and July 2018 were the highest since records began in 1981.
- The sea level around Ireland has risen by approximately 2–3 mm per year since the early 1990s.
- Compared with the 1981–2010 period, sea surface temperatures at Malin Head, County Donegal, were 0.47°C higher between 2010 and 2019.

To acquire national-level climate projection data, a form of model downscaling is usually required. Nolan and Flanagan (2020) produced a series of high-resolution climate projections for Ireland using a multi-model ensemble approach based on RCMs. These allow a greater level of spatial resolution and incorporation of topographical features than global climate models. Model simulations were run at high spatial resolutions of 3.8 and 4 km^2. All simulations used 1981–2000 as the reference period and were run for the future period of 2041–2060, referred to in this report as the *medium term* (following IPCC (2021a)). It should be noted that these simulations are not directly comparable with those outlined in Table 3.1, which use a baseline period of 1850–1900 and a global climate model approach. To account for potentially different GHG emission pathways, two RCP scenarios were used in the simulations, RCP4.5 and RCP8.5. Again, these are not directly comparable with the combined SSP–RCP scenarios used in the IPCC sixth assessment reports, but they are most closely aligned with SSP2–4.5 and SSP5–8.5, respectively. In this section some key trends as outlined by these simulations are explored; for detailed information see the original work (Nolan and Flanagan, 2020).

National-level climate simulations project that by the medium term annual temperatures will have increased by 1–1.2°C and 1.3–1.6°C under the RCP4.5 and RCP8.5 scenarios, respectively (Nolan and Flanagan, 2020). These values are somewhat lower than the median projected increases for the northern Europe region based on the latest IPCC analysis (Table 3.1), but the increasing trend is in agreement. Importantly, at a national level there is predicted to be a strong gradient in annual temperature increases from west to east of the country, with the largest temperature increases in the east. In terms of maximum temperatures, it is projected that by mid-century these will have increased by 1.0–2.2°C compared with 1981–2000. In line with the latest IPPC regional projections, national simulations project a significant reduction in the number of frost days of 45% and 58% under the RCP4.5 and RCP8.5 scenarios, respectively, by mid-century (Nolan and Flanagan, 2020). There are also projected increases in the occurrence of heatwaves, calculated as the number of heatwave events over a 20-year period, by 1 to 8 events per 20 years under RCP4.5 and by 3 to 15 events under RCP8.5. Importantly, increases in heatwave occurrence show strong regional trends and will be greatest in the south-east of the country.

National-level climate simulations project that by mid-century annual precipitation will increase slightly, by 0–6%, under RCP4.5 (Nolan and Flanagan, 2020). However, it must be noted that there was a higher level of disagreement between models used in the RCM-Ensemble for the direction of change and magnitude of change for annual precipitation than for trends in temperature variables (Nolan and Flanagan, 2020). This is in contrast to the latest projections for northern Europe from the IPCC, which project significant increases in annual precipitation across all scenarios and time periods (Gutiérrez *et al.*, 2021) (Table 3.1).

Uncertainty around precipitation trends in national-level climate simulations means that a breakdown of regional trends across Ireland may be less reliable. One of the suspected drivers of uncertainty regarding changes in annual precipitation at the national level is the projected increase in precipitation pattern variability. This increase in variability will also impact the effect that climate change has on ecosystem functioning. However, there were some stronger and more consistent signals at the seasonal level, with a substantial drying trend during summer (Nolan *et al.*, 2013). It is projected that during the summer months decreases in precipitation will range from 0–11% under RCP4.5 to 2–17% under RCP8.5. This suggests that there is likely to be an increased occurrence of drought events; however, caution is required here based on the *low confidence* in the direction of change regarding agricultural and ecological droughts for the northern Europe region in the latest IPCC projections for the same period (Gutiérrez *et al.*, 2021). Importantly, national simulations project that by mid-century there will be large increases in the occurrence of both dry periods and heavy precipitation events (Nolan and Flanagan, 2020).

Due to the combination of higher mean annual temperatures and a reduction in the number of frost days, by mid-century the length of the growing season[8] in Ireland is projected to increase by between 12% (under the RCP4.5 scenario) and 16% (under the RCP8.5 scenario) (Nolan and Flanagan, 2020). This, combined with increases in atmospheric CO_2 concentrations, will have an impact on ecosystem functioning and could lead to increased levels of gross primary production[9] on an annual basis. However, this must be considered in the light of simultaneous changes in climatic variability over the same period and an increased occurrence of extreme events such as heatwaves and heavy precipitation events, which are likely to dampen increases in gross and net primary production.

In summary, the key projected changes in the medium term (2041–2060) compared with 1981–2000 (Nolan and Flanagan, 2020) are:

- Annual temperature is projected to increase by 1.0–1.2°C under RCP4.5.
- Maximum temperatures are projected to increase by 1.0–2.2°C under RCP4.5.
- Heatwave events are projected to increase by the middle of the century, with the largest increases in the south-east.
- Number of frost days is projected to decline by 45% under RCP4.5.
- Annual precipitation is projected to slightly decrease, but there was significant disagreement between RCMs included in the ensemble.
- Summer precipitation is projected to decrease by 0–11% under RCP4.5 and by 2–17% under RCP8.5.

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[8] Where the growing season within a period of 12 months is defined as the number of days between the first occurrence of at least 6 consecutive days with a daily mean temperature of > 5°C and the first occurrence of at least 6 consecutive days with a daily mean temperature of < 5°C (Nolan and Flanagan, 2020).

[9] Gross primary production is defined as “the total amount of carbon fixed by photosynthesis over a specific time period” (IPCC, 2019b). This is distinct from net primary production, which is defined as “the amount of carbon accumulated through photosynthesis minus the amount lost by plant respiration over a specified time period that would prevail in the absence of land use” (IPCC, 2019b).

- Heavy precipitation events (frequency) are likely to increase by 5–19% by mid-century.
- Growing season – projected to increase by 12%; however, this does not consider the impact of simultaneous increases in climate variability.

3.1.4 Note on regional climate models

The use of RCMs and other processes for downscaling climate projections adds further sources of uncertainty to simply that of different forcing scenarios (Giorgi, 2019). Essentially, the RCM uncertainty is nested within the global climate model uncertainty. Therefore, downscaling generally increases rather than decreases overall uncertainty in regional projections (Giorgi, 2019). An understanding of this added uncertainty in relation to RCM projections is important when using such modelling to develop regional climate impact assessments. This uncertainty is also affected by the complexity of the region being modelled. At the same time RCMs have advanced significantly in the last decade and allow a level of spatial differentiation far beyond what is possible using a global climate model (Nolan and Flanagan, 2020). A fine-scale resolution is required to best incorporate local geophysical characteristics into projections, as well as to inform regional climate action. Therefore, further development of RCMs is important.

3.1.5 Atmospheric CO_2 concentration

The globally averaged concentrations of CO_2 reached a new high of 413.2 ppm in 2020 (WMO, 2021). While the focus of this chapter has been on the impact of CO_2 as a GHG and the role it plays in global warming, its concentration in the atmosphere also has a profound direct impact on plant growth and photosynthesis. Projected changes in plant function due to an increase in CO_2 will impact local and regional hydrological cycles and feed back to the global climate system (Jia *et al*., 2019). In general, increased CO_2 concentrations can be expected to result in enhanced rates of photosynthesis through what is termed CO_2 fertilisation (Chapin III *et al*., 2011). However, the actual extent to which CO_2 fertilisation can increase net primary productivity is co-determined by the availability of nutrients and water required for the photosynthetic process (Chapin III *et al*., 2011). There is *medium confidence* that since the 1980s the net strength of the land carbon sink provided by vegetation has been strengthened due to CO_2 fertilisation (IPCC, 2021a). However, recent analysis suggests that there could be a decline in global CO_2 fertilisation effects already occurring due to nutrient and soil moisture limitations on plant growth (Wang *et al*., 2020), although the analysis comes with some uncertainty due to limitations regarding the use of satellite data to accurately track changes in net primary productivity (Frankenberg *et al*., 2021).

Simultaneously, increased CO_2 concentrations result in increased efficiency with which plants can take up CO_2 during photosynthesis and so reduce the amount of water vapour lost during the gas exchange process (Hatfield and Dold, 2019). This phenomenon is expected to increase water use efficiency, which is becoming increasingly important in both natural ecosystems and managed ecosystems because of the increased occurrence of drought events in many regions. However, the latest global assessment from the IPCC (2021a) indicated *low confidence* that the increase in plant water use efficiency due to higher atmospheric CO_2 concentration alleviates extreme agricultural and ecological droughts.

Over longer timescales, the potential beneficial effects of CO_2 concentration increase on the land sinks' capacity to absorb carbon and co-benefits for water use efficiency may be diminished due to overall changes to the climate system. The land and ocean sinks absorb more CO_2 under high emissions scenarios than under low emissions scenarios; however, there is *high confidence* that at higher CO_2 levels both the ocean and land sinks become less efficient because of sink saturation processes (IPCC, 2021a). There are also numerous potential negative feedbacks from climate change on the functioning of terrestrial and aquatic ecosystems that are highly likely to impact on their overall functioning.

3.2 Climate Change Impacts on Ecosystem Functioning

The degree of impact due to an extreme climate event will differ depending on the ecological level of organisation within an ecosystem (Felton and Smith, 2017). Ecological studies focused on climate change often analyse only one ecological level rather than multiple levels within an ecosystem. Investigating effects across multiple levels is important, as the levels interact with each other and can affect the overall productivity of an ecosystem in relation to an extreme climate event (Felton and Smith, 2017). This section outlines a high-level review of climate impacts on ecosystem function with specific focus on studies that are relevant to the land system in Ireland. For details of the literature search methodology used in this chapter, see Appendix 2.

3.2.1 Climate impacts on grasslands

Owing to the highly interactive nature of precipitation, nutrient cycling and grazing in grassland ecosystems, changes to any of these key drivers will affect overall ecosystem function (McNaughton *et al*., 1982). In terms of climate change impacts on grasslands, changes to precipitation patterns and the occurrence of drought or heavy rainfall events are likely to have significant negative impacts on grassland primary productivity and therefore impact forage availability for livestock production in managed systems.

Drought events have been shown to result in decreases in grassland biomass yield across a wide range of natural and managed systems (Gilgen and Buchmann, 2009; Grime *et al*., 2000; Haughey *et al*., 2018; Vogel *et al*., 2012). The magnitude of the reduction in plant growth is influenced by a range of factors including the severity of the drought, timing of the event, plant species composition and functional traits, and soil water retention characteristics (Knapp and Smith, 2001; Olesen *et al*., 2011). In the case of managed grasslands, the grazing intensity interacts strongly with drought response, with for example more frequent mowing associated with a decrease in drought resistance (Vogel *et al*., 2012). An increase in summer droughts will affect grassland production to varying degrees across Europe, as drought can affect grass establishment and regrowth after its first cut (Olesen *et al*., 2011). Importantly, from an adaptation perspective, multispecies grassland swards have the potential to improve resistance and resilience to drought events (Grange *et al*., 2021; Hofer *et al*., 2016) and increase yield stability over time (Haughey *et al*., 2018).

The impacts of increasing annual or seasonal precipitation levels on grassland functioning are less well understood. However, more extreme and heavy rainfall events are likely to reduce soil trafficability[10] and increase the risk of negative impacts on soil functionality. This includes the risk of soil compaction, which is significantly increased when soil is wet (Posthumus *et al*., 2009). In grassland systems the action of livestock hooves on saturated soil can lead to poaching of the soil, rendering it susceptible to erosion and reducing its productivity. While subsurface compaction on grassland and cropland soils can occur due to the action of machinery traffic at any time, this is exacerbated by wet soil conditions (Creamer *et al*., 2010; Vero *et al*., 2014). Therefore, grazing management is likely to be increasingly impacted by extreme precipitation events. This could necessitate more frequent housing of livestock, and cattle in particular, for periods during the grazing season, resulting in a negative impact on grass utilisation, which is a key factor in the production efficiency of grassland systems in Ireland (O’Donovan *et al*., 2018).

However, at the same time it is projected that there will be a significantly longer growing season in Ireland by mid-century (see section 3.1.3). While the growing season projections are based solely on temperature, this does not include the time lag between temperature increase and plant growth required to support grazing. Neither does it include soil moisture levels, which also directly affect plant growth as well as soil trafficability. Including these factors produces a *grazing season* metric that is more appropriate to projections concerning agronomic grasslands (Smith, 1976; Collins and Cummins, 1996). Using such an approach, Nolan and Flanagan (2020) projected that the grazing season duration in Ireland (averaged over the whole country) will increase by 37 and 45 days per year by mid-century under RCP4.5 and RCP8.5, respectively.

Changes in climate will also have an impact on species composition and dominance in both semi-natural and managed grasslands. Experimentation has shown that shifts in climate zones can have strong impacts on grassland plant species composition (Sebastià *et al*., 2008). Poleward shifts in climate patterns globally have already been observed and are projected to continue (IPCC, 2021b). Improved grasslands commonly contain a dominant grass species that has been sown for improved productivity and other functional traits such as digestibility by livestock. In Ireland the primary grass used for intensive forage production is perennial ryegrass

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[10] Soil trafficability is defined as the capacity of soil to physically support agricultural traffic (livestock, humans and machinery) without causing soil or ecosystem degradation (adapted from Müller *et al*. (2011)).

(*Lollium perenne*) (O'Mara, 2008). However, in comparison with other grass species, its lack of resistance to environmental stress is a concern and may necessitate the exploration of alternative species or new cultivars under future climate conditions (Humphreys *et al*., 2006).

The reduced performance of the dominant grass species due to extreme weather events can affect the larger community within the ecosystem, by for example facilitating an increase in secondary species (Felton and Smith, 2017). It is also important to note that species with specific functional roles at community level have the potential to alter larger-scale ecosystem responses despite accounting for only a small proportion of overall plant composition, e.g. nitrogen-fixing legumes (Felton and Smith, 2017). Another example is the role of invertebrates in grasslands; invertebrate responses to changing precipitation patterns often mirror those of the plants within an ecosystem as a result of their role in pollination and nutrient cycling and therefore should also be considered when studying climate–agriculture relationships (Barnett and Facey, 2016).

3.2.2 Climate impacts on wetland/peatland

Peatlands cover 3% of the world's surface but contain as much carbon as stored by global vegetation (FAO, 2020c). When rates of vegetation productivity are greater than rates of vegetation removal or decomposition, there is a net accumulation of SOC. Peat deposits are the result of this process over time (Moomaw *et al*., 2018). Decomposition in wetlands and peatlands is limited due to lower temperatures, soil saturation and therefore low oxygen (Moomaw *et al*., 2018). Changes in rainfall patterns and an increase in temperatures will affect wetland and peatland carbon cycling due to increases in evapotranspiration and flooding events (Moomaw *et al*., 2018). It is expected that an increase in global temperatures will increase the decomposition rate of wetland SOC in the soil surface, suggesting an overall negative climate feedback to climate change from peatlands (Charman *et al*., 2013; Moomaw *et al*., 2018).

Peatlands store large quantities of SOC as well as providing important habitats for species, making peatlands important for both climate change mitigation and biodiversity (Carroll and Noss, 2021; FAO, 2020c). However, if peatlands become degraded through land use change, they have the potential to act as large sources of GHG emissions in the form of CO_2 and dissolved carbon in rivers (FAO, 2020c; Limpens *et al*., 2008; Moomaw *et al*., 2018). Moreover, peatlands store and slowly release water, which is an important ecosystem service in the face of increasing extreme rainfall events due to climate change (Miralles-Wilhelm, 2021). However, the ability of peatlands to carry out ecosystem functions such as water storage depends on the health of the habitat. Peatland that is degraded and/or in the process of restoration will be less effective in this function (Miralles-Wilhelm, 2021).

It is reported that 15% of peatlands across the globe have been drained for extraction (for use as fuel) and to make way for other land uses such as forestry (FAO, 2020c). Günther *et al*. (2020) found that almost all of the peatlands across the globe would have to stop emitting CO_2 if global climate neutrality is to be achieved by 2050. Peatland restoration is expected to be an important GHG mitigation strategy as countries move towards net-zero emissions targets (Glenk *et al*., 2021). Nature-based solutions for peatland restoration include establishing peatlands as protected areas and, if this is already the case, continuing and/or improving the enforcement of protections (Miralles-Wilhelm, 2021). For considerably degraded peatlands, the main actions required for restoration are rewetting and re-establishment of native flora (Miralles-Wilhelm, 2021).

The rewetting of peatland (which involves increasing the height of the water table), particularly artificially drained peat on cutaway bogs, can play an important role in climate change mitigation (Miralles-Wilhelm, 2021; Wilson *et al*., 2013). Rewetting results in the re-establishment of natural hydrological conditions in peatlands, which in turn reduces CO_2 emissions from the peat but can also increase CH_4 emissions, so consideration of site-specific characteristics and time since restoration is important for understating the climate mitigation potential of these systems (Evans *et al*., 2021; Jovani-Sancho *et al*., 2021). The recolonisation of native flora to peatland also enhances carbon sequestration and SOC storage (Wilson *et al*., 2013). The restoration of peatlands also has additional benefits to carbon storage, including biodiversity and air quality, since rewetting reduces fire risk (Miralles-Wilhelm, 2021; Page *et al*., 2009). The increased occurrence of extreme climate events under future climate scenarios is also an important consideration, as changes to the key environmental variables driving carbon uptake and GHG release, such as temperature and water table levels, can have significant impacts on the net GHG flux of these ecosystems (Helfter *et al*., 2015; Rinne *et al*., 2020).

3.2.3 Climate impacts on forestry/woodland

Climate change is projected to result in reduced net primary productivity in forests and woodlands due to, for example, an increase in the occurrence and severity of drought stress and wildfires (IPCC, 2019c). Biotic factors affecting forests, such as disease and pests, are also predicted to change as temperatures increase (Anderegg *et al*., 2020). Physical and biotic risks to forests should be considered when forests are included in nature-based climate solutions (Anderegg *et al*., 2020). The use of long-term satellite records and forest plot data can help estimate stresses and disturbances due to climate change (e.g. tree mortality and reductions in productivity) (Anderegg *et al*., 2020).

The majority of plantation forests in Europe are intensively managed, and adaptive management strategies will have to consider whether to continue with predominantly planting tree species with high economic value (e.g. Sitka or Norway spruce) or consider a mix of tree species that may be better suited to changing climatic conditions or have increased resistance to extreme events (Lindner *et al*., 2010). At a regional level (e.g. western Europe), forestry management can also feed back to the climate system itself, which should also be considered in high-level forest strategies and management plans (e.g. at a European level). For example, evapotranspiration from forests during the growing season can cool the land surface at a regional level, while in the dormant season forests are warmer than any other form of land cover (Jia *et al*., 2019).

The IPCC (2019c) reports that limited information is available on sustainable forest management globally and that this also contributes to the loss of forests and reduction in tree cover. However, an example of policy action for sustainable forest management is REDD+ (Reducing Emissions from Deforestation and Forest Degradation), a voluntary framework by the UN to reduce emissions in developing countries through the development of national forestry strategies or action plans and increasing the role of sustainable management of forests, conservation and enhancement of forest carbon stocks (FAO, 2020b).

3.2.4 Climate impacts on cropland

Croplands cover 12–14% of the world's ice-free land area (IPCC, 2019c) and are particularly vulnerable to land degradation due to unsustainable land management, which is increasingly compounded by climate change (Olsson *et al*., 2019). Avoiding land degradation is important for maintaining crop production potential, as well as for a wide array of key soil functions, including the ability to store carbon. Of the different categories of managed land, cropland is the most frequently impacted by increasing temperatures and extreme weather events (Baumbach *et al*., 2017; IPCC, 2019c). Global warming of even 1.5–2°C poses significant risks to the production of many crops and is likely to result in disruptions to regional and global food systems (IPCC, 2019c). Crops are uniquely vulnerable to changes in rainfall frequency, atmospheric and soil temperatures and extreme weather events such as drought or flooding, all of which can negatively impact plant growth (Praveen and Sharma, 2019). Climate change can also indirectly affect crop growth by altering disease and pest life cycles. Fluctuations in precipitation and temperatures can also influence the effectiveness of chemical inputs in crop systems, which has environmental consequences.

In Ireland, projected increases in the length of the growing season, in a similar fashion to grassland agriculture, could have a positive impact on crop production. Although a longer growing session may have benefits in terms of crop production, there will also be negative impacts. Drought and heatwave events are expected to reduce yields, and there are likely to be complex interactions between changing precipitation patterns and crop performance. In the case of tillage, the trafficability of soil, which is related directly to soil moisture content, as well as soil physical characteristics, is a key determinant of when crop management activities can be carried out with machinery. A more unpredictable climate will pose challenges for these operations and will likely require significant adaptation.

For crops the metric usually used to model such effects is the change in growing degree days.

The growing degree day metric incorporates the temperature required for crop growth and development, and the requirement to move across various crop development phases until harvesting occurs. This can also be used to investigate the potential for insect and pest pressures, which are also highly dependent on temperature and the daily accumulation of heat energy over the growing season. Different crops have different growing degree day requirements. For example, wheat and barley have a 5.5°C threshold, below which development and growth phase progression do not occur (Nolan and Flanagan, 2020). The projected higher temperatures by mid-century will result in an increase in growing degree days and could be positive for crop development. However, there will also be an increase in the associated pest and disease pressures on the main crops, which may limit the overall impact of any benefits (Nolan and Flanagan, 2020). Furthermore, the increase in growing season needs to be considered in the light of projected increases in extreme climate events, which could significantly disrupt crop production. As temperatures increase, the crop growing season will start earlier in the year and crops will be more at risk of delayed frost events (Baumbach *et al*., 2017).

Models such as WTGROWS, IFOCROP and DSSAT, along with soil assessments, have been used to study the responses of crop yields to increasing global temperatures (Praveen and Sharma, 2019). In Ireland, a global temperature increase of 1.6°C has been projected to cause an increase in barley grain yield, with possibly a greater increase in the west of Ireland (Holden *et al*., 2003). However, for some crops, such as potatoes, non-irrigated crop systems could become unviable for Irish farmers because of increases in temperature and reductions in summer precipitation (Holden *et al*., 2003). Possible cropping solutions to climate change include selecting more drought-resistant varieties, changing cropping patterns and using cover crops (Praveen and Sharma, 2019).

Management practices to reduce carbon loss from croplands include the retention of crop residues, increased cropping frequency, reduced tillage and no-tillage (Abdalla *et al*., 2014; Luo *et al*., 2010; Tiefenbacher *et al*., 2021). Cover crops combined with reduced tillage have also been proven to increase SOC. When zero- or no-tillage practices are combined with retaining crop residues, this can also sequester more carbon and increase water and nutrient use efficiency in the soil (Hussain *et al*., 2021). Luo *et al*. (2010) found that converting from conventional tillage to no-tillage management significantly changed the distribution of carbon in the soil profile; however, the conversion increased the SOC in double cropping systems only. Mean annual temperature, mean annual rainfall, nitrogen fertilisation and duration of adopting no-tillage were found to have no effect on the response of SOC when land was converted from conventional tillage to no-tillage (Luo *et al*., 2010).

3.2.5 Water quality and aquatic ecosystems

Rising global temperatures are predicted to accelerate the global hydrological cycle and water-holding capacity of the atmosphere (Blöschl *et al*., 2019; Reid *et al*., 2019). Impacts of climate change on coastal and marine ecosystems include rising sea levels, increased CO_2 levels in the water and changes in the pH of water (Reid *et al*., 2019; Ummenhofer and Meehl, 2017). Extreme weather events for marine ecosystems are also expected to increase, including more frequent and intense storms, extremes in wave activity and sea levels, and changes in salinity (FAO, 2011; Ummenhofer and Meehl, 2017). Marine heatwaves, described as extreme temperature events, can affect local species populations and species range and have economic effects on aquaculture and the marine fishing industries. Marine heatwave events are reported to have occurred more frequently in the past few decades, and this is expected to continue to increase as global atmospheric temperatures rise (Ummenhofer and Meehl, 2017). It is expected that human responses to increased temperatures will also have secondary effects on fisheries, including water diversion and collection, due to an increased demand for freshwater (Ficke *et al*., 2007).

Direct climate change impacts on freshwater ecosystems include an increase in water temperatures, lower dissolved oxygen levels, changes in the transmission of waterborne diseases, stresses due to toxic substances and pollution, and changes in water depths (Ficke *et al*., 2007; Woolway *et al*., 2020). All of these are likely to contribute to the decreased productivity of fish populations in freshwater ecosystems. In rivers, decreased stream flow in summer will also have impacts on water availability, water quality, fisheries and the recreational use of freshwaters (Steele-Dunne *et al*., 2008). The surface water temperature of lakes has increased at a similar rate to global air temperature trends, which has also resulted in less ice cover on lakes in the northern hemisphere in winter (Woolway *et al*., 2020). Ice cover, wind speeds and solar radiation levels are predicted to increase global freshwater lake evaporation rates by 16% by 2100 (Woolway *et al*., 2020). Freshwater ecosystems are also impacted by drought events, which can degrade water quality, reduce habitat availability and alter biotic interactions. Freshwater salinisation is predicted to intensify, particularly in drier climates where evaporation rates may increase (Reid *et al*., 2019). Rising water temperatures can increase the occurence of algal blooms, which can reduce dissolved oxygen availability or produce toxins, subsequently impacting higher trophic levels, such as fish kills (Reid *et al*., 2019).

Climate change projections include more frequent floods in north-west Europe as a result of an increased occurrence of heavy precipitation events. Flood risk management strategies, particularly for medium to large catchment areas, will be important to adapt to this increase in flood discharge (Blöschl *et al*., 2019). Short, intensive precipitation events will also have a direct impact on urban water quality depending on the drainage systems in place (Whitehead *et al*., 2009). Water pollution is a significant threat to global food security, and contaminated freshwater from agricultural sources, transported following flood events, can alter the dissolved organic carbon and nitrogen levels in marine and freshwater systems (FAO, 2011; Smith and Cave, 2012).

3.2.6 Infrastructure and technogenic surfaces

Urban development affects local soils through soil sealing, densification, excavation and pollution (Lal *et al*., 2021). Soil sealing is defined as the permanent covering of land and its soil with an impermeable material such as concrete or asphalt (European Commission, 2012). Soil sealing affects ecosystem services, reducing the potential for food provisioning services; reduces space for nature, impacting on urban biodiversity; prevents or severely reduces interactions between soils and atmosphere; and causes disruption to the hydrological process. Soil sealing also affects macro- and micro-biodiversity within the soil profile and impacts the resistance of soil biota to environmental pressures (European Commission, 2012; Fikri *et al*., 2021). Soil sealing can also directly contribute to the “urban heat island” effect due to a reduction in evapotranspiration and an increase in absorption of heat energy by artificial surfaces (e.g. roofs and roads) in urban areas. Generally, soil sealing is associated with lower vegetation cover and therefore has negative impacts on ecosystem services, such as air quality benefits, provided by plants and trees (Lal *et al*., 2021). Where soil sealing occurs, mitigation measures to maintain some soil functions are important, for example using permeable materials (European Commission, 2012). As soil sealing is mostly attributed to land planning decisions, spatial planning to limit soil sealing should involve an integrated approach with all relevant public authorities and not just environmental departments (European Commission, 2012).

The expansion of urban areas using impermeable materials for infrastructure has a direct impact on the amount of rainfall that can be absorbed by soils. For example, extreme precipitation events can overwhelm drainage systems and lead to flooding, especially where maintenance of drainage infrastructure is not carried out regularly or the drainage system is not suitable for altered climatic conditions. This has a negative impact on the capacity of the land to cope with run-off from precipitation events – which are expected to intensify and increase in frequency (European Commission, 2012). In an agricultural context, run-off is typically a mix of surface materials, sediment and faeces, making its contents similar to those of diluted slurry or soiled dairy waters (Fenton *et al*., 2021). Soil sealing on farms through the construction of infrastructure can increase run-off and impact local water sources. Natural landscape features such as adjacent fields and drainage ditches can be used to reduce the amount of run-off reaching water courses; however, management options for intercepting run-off should be specific to individual cases/farms (Fenton *et al*., 2021).

The Food and Agriculture Organization of the United Nations (FAO) defines technosols as “soils of urban, industrial, traffic, mining and military areas which have been drastically changed by anthropogenic activities” (FAO, 2019). There are four main types of technosols; soils sealed by “technic hard” materials such as concrete or asphalt; soils including greater than 20% of artefacts in the top 1 m of the soil profile; constructed soils or naturally developed shallow soils on buildings that do not have contact with any other soil materials; and soils with geomembranes or other synthetic materials (FAO, 2019). The definition of "technosols" varies across the literature and often excludes its value as a resource for ecosystem services in the urban environment (Rodríguez-Espinosa *et al*., 2021). Ecosystem services provided by technosols can differ widely from those provided by natural soils and are often not as efficient (FAO, 2019). However, urban soils can support other natural resources such as urban trees and public green spaces (Lal *et al*., 2021; Rodríguez-Espinosa *et al*., 2021).

Urban sprawl and increases in low-density settlements constitute one of the biggest threats to sustainable land development in Europe (European Commission, 2012). Soil disturbance is involved in building activities that typically include removing topsoil, which usually contains a large proportion of soil carbon stocks. Abu-hashim *et al*. (2016) found that land use change of cropland through encroachment of urban areas in the Mediterranean region was approximately 15% from 1990 to 2015. The change in land use from arable to urban resulted in a reduction of 285 kt C of SOC. However, there is still potential for soil carbon storage in technosols (Vasenev *et al*., 2018). Urban areas have been found to contain a moderately high SOC stock and, importantly, may have the potential to act as SOC sinks if managed appropriately (Xiong *et al*., 2014).

4 Land Use Scenarios for Net Zero

The objective of this chapter is to explore a set of indicative land use change scenarios and their capacity to facilitate net-zero GHG emissions from the AFOLU sector in Ireland by 2050. Scenarios are informed by the imperative to reach net zero and subject only to biophysical constraints, i.e. they are not projections based on socioeconomic modelling, but rather take a foresight approach commensurate with the necessarily ambitious objective. As set out in Chapter 2, overall the AFOLU sector is a significant GHG source for Ireland and therefore there are considerable challenges associated with reaching net zero. Numerous potential response options could be undertaken for climate mitigation in the land system in Ireland (see Haughey (2021)); however, here we focus on only a subset. These include afforestation, peatland and organic soil restoration, agricultural optimisation, space for nature, space for bioenergy and additional cropland. To enable a set of simplified land use scenarios to be developed, a set of baseline assumptions must be made. We note that these assumptions have a level of uncertainty associated with them (see section 4.1). A key baseline determinant in this process is the net-zero target for the AFOLU sector by 2050, which is a policy target set as part of this project scope (see Information Box 4.1 for discussion).

The scenarios developed here are by no means exhaustive but represent a set of potential pathways to net zero. Where possible we have explored the actions contained within scenarios separately and then in combination. This allows a separate analysis of individual and combined potential for climate mitigation across key actions represented in each of the scenarios. In the case of three scenarios (S5, S6 and S7), these are dealt with as add-on actions to previous combinations. This is because the primary objective of the initial set of scenarios (S1 to S4) is to achieve net-zero emissions from the AFOLU sector by 2050, while the add-on scenarios (S5 to S7) are targeted at providing additional ecosystem and provisioning services.

4.1 Baseline Assumptions

This section provides an overview of the basic assumptions on which the scenarios are based, as well as detailed descriptions of each scenario in terms of land use change and impact on GHG emissions.

Scenario permutations in the AFOLU sector until 2050 were derived based on seven core scenarios developed in consultation with project stakeholders (Table 4.1), using 2018 national inventory emissions and land area data as a baseline. The results are presented as changes in the land areas by 2050 (Tables 4.2 and 4.3), and resulting GHG fluxes (Tables 4.4 and 4.5), in relation to achieving the target for climate neutrality by the year 2050.

Some important baseline assumptions:

- grassland area approximately 4200 kha;
- forestry area approximately 770 kha;
- approximately 335 kha of organic soils under grass is drained;
- approximately 70 kha of exploited (drained) raised bog;
- approximately 1.37 million dairy cows and 0.98 million suckler cows.

A very simplistic "business-as-usual" (BAU) trajectory is included for reference, based on the average afforestation rate over the past 10 years (Table 4.1).

The mineral SOC sink under improved grassland is assumed to fall out of inventory calculations by 2050 on the basis that continued expansion of improved grassland for livestock production is incompatible with the climate neutrality objective.

New organic soil emission factors under forestry have been included (Jovani-Sancho *et al.*, 2021), leading to additional emissions of almost 2 Mt CO_2eq annually from the forest estate.

HWP carbon storage is not accounted for, because (1) limited data are available on future HWP sink in forestry results extracted from the GOBLIN v1.0 model used for this analysis; and (2) the projected HWP sink by 2030 of approximately 2.8 Mt CO_2eq constitutes approximately 10% of current non-AFOLU

Information Box 4.1. Net-zero ambition for the AFOLU sector

Stabilising the global climate system and halting global warming necessitate substantial reductions in CH_4 and N_2O emissions from the AFOLU sector, along with net CO_2 sequestration to offset residual long-lived GHG emissions (IPCC, 2018; Prudhomme *et al.*, 2021; Tanaka and O'Neill, 2018). The EU has adopted a Climate Policy Carbon Budget approach with regard to achieving its stated climate mitigation objectives. This is distinct from tying mitigation targets to specific global warming levels, such as the global warming limits set out in the Paris Agreement (McGuire *et al.*, 2020). Instead, this approach means that the budget is set relative to the decarbonisation trajectory of the country or region and allows for some flexibility in terms of what sectors are included. The ambition for climate action in the EU has been ramped up in recent years considering the latest scientific understanding of what needs to be done to limit global warming. This has led to the targeting of a 55% reduction in net emissions by 2030 compared with 1990 levels, with a view to staying on track for overall net zero by 2050 (European Commission, 2020a).

Ireland is committed to reaching net-zero GHG emissions by 2050, a goal that will require transformative and integrated action across all sectors. To reach this national objective, there is a strong case to be made for achieving at least net-zero emissions in the AFOLU sector. This is also in line with EU targets for the AFOLU sector, and as part of the "Fit for 55" legislative package the European Commission is proposing an increase in carbon removals to achieve climate neutrality in the combined AFOLU sectors by 2035 (European Commission, 2021a). At the national level, the mitigation ambition for the AFOLU sector has impacts on the required level of mitigation across other sectors. For example, if a target of less than net zero was set, this would require other sectors to take up the slack to meet national targets – an almost impossible task given that AFOLU is the only sector in which scalable CO_2 removals are currently possible. Undoubtedly, as outlined in Chapter 2, this poses a significant challenge since the agriculture and LULUCF categories are both GHG emission sources at present. Yet the targets already required for other sectors are also highly ambitious; for example, under the 2021 Climate Action Plan the goal for electricity generation is to achieve 80% renewable electricity by 2030, and for transport the goal is a reduction of 42–50% of GHGs by 2030 (DECC, 2021).

The Paris Agreement is predicated on territorial responsibilities for climate action in line with global climate stabilisation objectives. While considerable debate remains about whether producers or consumers should be responsible for GHG emissions, climate change is a grand societal challenge, and effective long-term climate action requires government coordination and associated democratic accountability. Arguably, most of Ireland's AFOLU sector emissions are exported abroad along with its milk and beef products, but, conversely, Ireland imports huge volumes of embodied emissions in cars, clothing, animal feed, food products, and so on. However, while there is an established framework for global GHG accounting at the national scale, there remains a lack of harmonisation and agreement on methodologies for the full accounting of emissions at the value-chain (product) level. Even if these accounting barriers were overcome, the scale of systemic economic transformation needed to stabilise the global climate simply cannot be achieved through uncoordinated, sporadic and short-term consumer choices (i.e. "the market"). Enabling the rapid and far-reaching transformation required to limit global warming necessitates change across the energy, land, urban, infrastructure and industrial systems (de Coninck *et al.*, 2018). In the energy system, for example, achieving sustainable levels of energy use requires incorporation and understanding of socioeconomic enabling factors (Vogel *et al.*, 2021). In the context of urgent climate action required to tackle the climate emergency, establishing territorial net-zero targets that rely on existing national accounting mechanisms is a realistic and sensible approach.

Ireland's agri-food export sector relies heavily on a clean and green image backed by marketing campaigns such as Origin Green (Bord Bia, 2017). If Ireland's commitment to climate stabilisation required by the Paris Agreement is brought into doubt, the credibility of Origin Green, and the wider sustainability credentials of Ireland's agri-food sector, could be seriously undermined. It can therefore be argued that the

Information Box 4.1. Continued

long-term economic profitability of the sector depends on operation within a net-zero national emissions envelope. To realise the objective of net-zero carbon emissions from Ireland's AFOLU sector will require transformative integrated action. It is essential that this commitment is addressed together with a range of other environment policy commitments related to air, water, soil, biodiversity and Sustainable Development Goals.

GHG emissions, representing a useful magnitude of additional CO_2 removal to offset residual emissions from the non-AFOLU sector in 2050 (as required to achieve territorial climate neutrality).

For the purposes of this report, analysis was undertaken in Microsoft Excel using baseline data from the national inventory report and simple extrapolations representing specified reductions in emissions as per the descriptions below (i.e. highly stylised scenarios based on a balance sheet approach, not model projections). Nonetheless, the forestry component of the scenarios relied on a projected net flux of emissions arising from the existing forest estate, onto which was superimposed a projection of the net flux arising from new forest planting (starting in 2025) at the rates described below. This required the use of scenarios modelled in GOBLIN v1.0, a biophysical land use emission model developed for Ireland and validated against the national inventory report and scaled according to the areas specified in this report. The model and its validation process are fully described in Duffy *et al*. (2022a) and a subsequent scenario paper (Duffy *et al*., 2022b). However, it should be noted that a significant reduction in the harvest interval across the private forest estate in recent decades has resulted in the forest stand age-profile represented in GOBLIN, based on historical management practices in the public forest estate, diverging from recent projections for forest fluxes based on national inventory report methodology. This is likely to have a stronger influence on short-term, rather than 2050+, projections, but nonetheless is a caveat to the net flux estimates applied to forests in 2050 in this report.

GHG balances are calculated based on GWP_{100} and CO_2eq values from the IPCC's fifth assessment report (AR5) (i.e. 28 for CH_4 and 265 for N_2O). Balances are presented with and without CH_4, accounting for a possible future policy shift towards separate accounting for CH_4.

4.2 Scenario Descriptions and Land Use Change

This section provides a brief description of each scenario in terms of both the rationale behind its inclusion and land use change. In this case land use change includes changes to the management of the land system as well as changes from one main category to another. Table 4.1 provides a summary of overall changes by scenario. Land use change relative to the 2018 baseline under each scenario is also provided, including and excluding CH_4 from the net-zero target for the AFOLU sector (Tables 4.2 and 4.3).

4.2.1 S1: increased afforestation

Afforestation is a key measure by which carbon can be sequestered in biomass and soils and in the form of HWPs. It has been identified as a climate response option with high applicability to the land system in Ireland, albeit with important caveats regarding sustainable deployment and management of forestry (Haughey, 2021). As noted above, it was not possible to include HWP carbon in this scenario analysis.

Currently (and see Chapter 6 for a detailed analysis), policy targets for the 2025–2050 period are afforestation at 8 kha per year. Following the work of Duffy *et al*. (2020, 2022a), approximate levels of afforestation required to meet net-zero targets were defined for this scenario as:

- 20 kha afforestation per year over 2025–2050 for net zero excluding CH_4;
- 35 kha afforestation per year over 2025–2050 for net zero including CH_4.

These afforestation rates along with the current policy target of 8 kha yr^{-1} form the basis for the two scenarios developed here for afforestation: S1a and S1b (Table 4.1).

Table 4.1. Summary of AFOLU scenarios in 2050, expressed in terms of change relative to baseline (2018)

		Agriculture					Baseline grassland area (%)		
Measure	**Scenario**	**Animal number change (%)**	**Emissions intensity change (%)**	**Restoration of exploited bogs (%)**	**Rewetting drained organic grasslands (%)**	**Afforestation rate (kha yr^{-1})**	**Space for nature**	**Bioenergy from grassland**	**Additional cropland**
None	BAU	0	0	0	0	5	0	0	0
Afforestation	S1a	0	0	0	0	8			0
	S1b	0	0	0	0	35/20	0	0	
Rewetting	S2	0	0	100	90	5		0	0
Agriculture optimisation	S3a	0	–30	0	0	5	0	0	0
	S3b	–30	–30	0	0	5	0	0	0
Combined	S4a	0	–30	100	90	8	0	0	0
	S4b	0	–30	100	90	35/20	0	0	0
	S4c	–30	–30	100	90	8	0	0	0
	S4d	–30	–30	100	90	35/20	0	0	0
+ Nature area	S5	–30	–30	100	90	35/20	10	0	0
+ Bioenergy	S6	–30	–30	100	90	35/20	0	10	0
+ Cropland	S7	–30	–30	100	90	35/20	0	0	10

Afforestation rates are presented as an annual average between 2025 and 2050, with maximum rates determined by removals needed for net zero in 2050 including and excluding CH_4 from GWP_{100} AR5 balance. For afforestation, 35 refers to 35 kha yr^{-1} required for net zero when CH_4 is included and 20 refers to 20 kha yr^{-1} required when CH_4 is excluded.

Table 4.2. Scenario area change results excluding CH_4 from GWP balance calculations (i.e. maximum afforestation rate of 20 kha yr^{-1})

	Land use (total change until 2050, kha)							
Scenario	Grassland	Rewetted grassland	Wetland	Forest	Space for nature	Bioenergy from grassland	Additional cropland	Stocking density change (%)
BAU	–125	0	0	125				3
S1a	–200	0	0	200				5
S1b	–500	0	0	500				14
S2	–497	302	70	125				13
S3a	–125	0	0	125				3
S3b	–125	0	0	125				–28
S4a	–572	302	70	200				16
S4b	–872	302	70	500				26
S4c	–572	302	70	200				–19
S4d	–872	302	70	500				–12
S5	–1292	302	70	500	420			1
S6	–1292	302	70	500		420		1
S7	–1292	302	70	500			420	1

Stocking density changes are also shown to indicate changes in grassland use intensity.

Table 4.3. Scenario area change results including CH_4 in GWP balance calculations (i.e. maximum afforestation rate of 35 kha y^{-1})

	Land use (kha total change until 2050)							
Scenario	Grassland	Rewetted grassland	Wetland	Forest	Space for nature	Bioenergy from grassland	Additional cropland	Stocking density change (%)
BAU	–125	0	0	125				3
S1a	–200	0	0	200				5
S1b	–875	0	0	875				26
S2	–497	302	70	125				13
S3a	–125	0	0	125				3
S3b	–125	0	0	125				–28
S4a	–572	302	70	200				16
S4b	–1247	302	70	875				42
S4c	–572	302	70	200				–19
S4d	–1247	302	70	875				0
S5	–1667	302	70	875	420			16
S6	–1667	302	70	875		420		16
S7	–1667	302	70	875			420	16

Stocking density changes are also shown to indicate changes in grassland use intensity.

Table 4.4. Scenario emission results excluding CH_4 from GWP balance calculations, with maximum afforestation of 20 kha yr^{-1}

	Emissions (kt CO_2 eq yr^{-1})							
Scenario	Agriculture	Organic soil	Wetland	SOC	Forestry (Conif_D)	Forestry (Broad_D)	Net balance (Conif_D)	Net balance (Broad_D)
BAU	6270	8904	2132	0	12	12	17,318	17,318
S1a	6270	8904	2132	0	–1260	–966	16,046	16,340
S1b	6270	8904	2132	0	–6347	–4878	10,958	12,428
S2	6270	902	3	0	12	12	7186	7186
S3a	4389	8904	2132	0	12	12	15,437	15,437
S3b	3135	8904	2132	0	12	12	14,183	14,183
S4a	4389	902	3	0	–1260	–966	4033	4327
S4b	4389	902	3	0	–6347	–4878	–1054	416
S4c	3135	902	3	0	–1260	–966	2779	3073
S4d	3135	902	3	0	–6347	–4878	–2308	–838
S5	3135	902	3	0	–6347	–4878	–2308	–838
S6	3135	902	3	0	–6347	–4878	–2308	–838
S7	3135	902	3	2,266	–6347	–4878	–42	1427

Net balance results complying with climate neutrality are shaded green. Two scenarios for afforestation are either conifer dominated (Conif_D) or broadleaf dominated (Broad_D), corresponding to a 70:30 or a 30:70 area split, respectively.

Table 4.5. Scenario emission results including CH_4 in GWP balance calculations, with maximum afforestation of 35 kha yr^{-1}

	Emissions (kt CO_2 eq yr^{-1})							
Scenario	Agriculture	Organic soil	Wetland	SOC	Forestry (Conif_D)	Forestry (Broad_D)	Net balance (Conif_D)	Net balance (Broad_D)
BAU	20,797	9168	2167	0	12	12	32,144	32,144
S1a	20,797	9168	2132	0	–1260	–966	30,837	31,130
S1b	20,797	9168	2132	0	–12,707	–9767	19,389	22,329
S2	20,797	1963	243	0	12	12	23,015	23,015
S3a	14,558	9168	2132	0	12	12	25,869	25,869
S3b	10,398	9168	2132	0	12	12	21,710	21,710
S4a	14,558	1963	243	0	–1260	–966	15,504	15,798
S4b	14,558	1963	243	0	–12,707	–9767	4057	6997
S4c	10,398	1963	243	0	–1260	–966	11,345	11,639
S4d	10,398	1963	243	0	–12,707	–9767	–102	2837
S5	10,398	1963	243	0	–12,707	–9767	–102	2837
S6	10,398	1963	243	0	–12,707	–9767	–102	2837
S7	10,398	1963	243	2266	–12,707	–9767	2164	5103

Net balance results complying with climate neutrality are shaded green. Two scenarios for afforestation are either conifer dominated (Conif_D) or broadleaf dominated (Broad_D), corresponding to a 70:30 or a 30:70 area split, respectively.

Key changes under S1a

- Change of land use 200,000 ha of additional forestry by 2050 (rate of 8000 ha y^{-1}) coming from the grassland category.
- Results in a 5% increase in average grassland livestock stocking density.

Key changes under S1b

- Change of land use 875,000 or 500,000 ha of additional forestry by 2050 (rate of 35,000 or 20,000 ha yr^{-1}) coming from the grassland category.
- Results in a 26% increase in average grassland livestock stocking density (scenario including CH_4).

We note that levels of land use change represent very significant increases on current actual rates of afforestation and would have impacts on many other provisioning and ecosystem services (see Chapter 5 for an analysis of impacts).

In addition, afforestation is modelled as either conifer dominant (Conif_D) or broadleaf dominant (Broad_D), namely a 70:30 or 30:70 ratio of coniferous to broadleaved species split by land area, respectively. In this case, the conifer-dominated scenario is more reflective of commercial forestry development as it currently stands, while the broadleaf-dominated scenario is more compatible with achieving co-benefits with ecosystem services goals such as biodiversity conservation and water quality. Note that in either scenario current forest is considered to remain in its current planting form and under current management, which is therefore conifer dominant.

4.2.2 S2: rewetting of peatland and used organic soils

Due to the significant area of degraded peatlands in Ireland (Figure 1.4), there is significant scope for restoration. Restoration has the potential to reduce GHG emissions from the AFOLU sector in the short term and could lead to the formation of long-term carbon sinks for centuries to come. There are also likely to be co-benefits for biodiversity and water quality. The restoration of peatlands has been identified as a climate response option with high applicability to the land system in Ireland, albeit with important caveats regarding site-specific challenges to successful restoration (Haughey, 2021).

In the development of scenarios, two types of peatland/organic soils were considered (Table 4.1). First, we consider the restoration of peatland that has been used for extraction but remains in the peatland land use category (referred to here as exploited peatland). We note that this analysis includes only exploited raised bogs and not blanket bogs, which account for a much larger area nationally. The estimated proportion impacted by past peat cutting is 48%, with less than 10% of this area estimated to have been impacted by mechanical extraction (Conaghan *et al.*, 2000). Second, we considered the rewetting (or, more precisely, raising the water level) of former peatlands that have been converted to grassland and are therefore accounted for under the grassland category (referred to here as organic soil under grassland). As noted in section 2.5, these organic soils under grassland account for highly significant sources of grassland emissions nationally. From these along with the baseline land use assumptions, S2 includes:

- 100% rewetting of exploited peatland by 2050;
- 90% rewetting of organic soil under grassland by 2050.

We note that this is modelled as a very ambitious upper bound for rewetting of drained organic soils under grassland, where various logistical and socioeconomic barriers may restrict 100% rewetting.

Key changes under S2

- 302,000 ha of grassland on organic soils rewetted successfully by 2050 (which is estimated as 90% of that category of current land use).
- 70,000 ha of exploited peatland rewetted successfully by 2050 (which is estimated as 100% of that category of current land use).
- Results in a 13% increase in average grassland livestock stocking density.
- Plus assuming BAU of 125,000 ha (rate of 5000 ha yr^{-1}) additional forestry by 2050 coming from grassland.

4.2.3 S3: agriculture optimisation

The focus of agricultural optimisation measures considered was on grassland livestock production systems. This is due to the dominance of grassland-based agriculture in Ireland in terms of land use, economic activity and GHG emissions. Increased food productivity, improved grazing land management and improved livestock management have been identified as three sets of climate response options with high applicability to the grassland system in Ireland (Haughey, 2021). Important caveats to that analysis include the need to factor in potential rebound effects[11] with regard to absolute emissions, which is particularly important in livestock systems (Mbow *et al*., 2019).

Two sets of optimisation actions were considered: first, a change in production efficiency in cattle and sheep management, and, second, a change in total numbers of cattle and sheep nationally (Table 4.1). With regard to production efficiency measures for agriculture, there is a very wide array of actions that could be undertaken in practice. As our focus is on the impact with regard to climate mitigation, only the overall target was specified and not the contribution of the individual actions. To include optimisation measures here a set of indicative levels was selected:

- 30% reduction in emissions intensity for cattle and sheep nationally by 2050;
- 30% reduction in total cattle and sheep numbers by 2050.

Clearly, many combinations are possible with regard to change within these two sets of measures. The 30% emissions abatement is considered a plausible but optimistic level of emissions intensity decoupling based on the widespread deployment of technical options currently available or on the horizon (Lanigan *et al*., 2019). These options include enteric CH_4 inhibitors such as 3-NOP, anaerobic digestion of manures, use of inhibited urea and substantial reductions in synthetic nitrogen application via the use of grass–clover swards, and low-emission slurry spreading to improve nutrient cycling. The 30% reduction in cattle and sheep numbers was selected because it demonstrates the large effect of ruminant livestock numbers on the mitigation measures required to achieve net zero. We note that this value is somewhat arbitrary, and it is used here for indicative purposes only. However, when combined with a 30% reduction in animal numbers, the 30% emissions abatement could drive agricultural emissions down by 50%, a magnitude commensurate with the 2050 climate neutrality objective and in line with the 2030 target for around a 20–30% reduction set out in the Climate Action Plan (DECC, 2021).

Key changes under S3a

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- No change in grassland livestock numbers.
- Plus assuming BAU of 125,000 ha (rate of 5000 ha yr^{-1}) additional forestry by 2050 coming from grassland.
- Results in a 3% increase in average grassland livestock stocking density.

Key changes under S3b

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- A 30% decrease in grassland livestock numbers by 2050[12].
- Plus assuming BAU of 125,000 ha (rate of 5000 ha yr^{-1}) additional forestry by 2050 coming from grassland.
- Overall results in a –28% decrease in average grassland livestock stocking density.

4.2.4 S4: combined S1–S2–S3

Under S4, there are combinations of the first three land use change scenarios:

- increased afforestation (S1);
- plus rewetting of peatlands and used organic soils (S2);
- plus agriculture optimisation (S3).

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[11] The rebound effect, or Jevons paradox, is defined as a lower than expected reduction or net increase in global resource use despite increases in resource use efficiency (for discussion, see Haughey (2021)).

[12] Represented simply as a 30% emissions reduction, which could equate to an equal 30% reduction across all animal categories, or various combinations across different categories that add up to a net 30% emission reduction. It was beyond the scope of this initial analysis to explore this in more detail.

Four permutations were modelled to reflect interaction across different levels of afforestation and agricultural optimisation which is included with and without change to cattle and sheep numbers (Table 4.1).

Key changes under S4a

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- No change in grassland livestock numbers.
- 302,000 ha of grassland on organic soils rewetted successfully by 2050 (which is estimated as 90% of that category of current land use).
- 70,000 ha of exploited peatland rewetted successfully by 2050 (which is estimated as 100% of that category of current land use).
- 200,000 ha of additional forestry by 2050 (rate of 8000 ha yr^{-1}) coming from the grassland category.
- Results in a 16% increase in average grassland livestock stocking density.

Key changes under S4b

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- No change in grassland livestock numbers.
- 302,000 ha of grassland on organic soils rewetted successfully by 2050 (which is estimated as 90% of that category of current land use).
- 70,000 ha of exploited peatland rewetted successfully by 2050 (which is estimated as 100% of that category of current land use).
- 500,000 or 875,000 ha of additional forestry by 2050 (planting rate of 20,000 or 35,000 ha yr^{-1}) coming from the grassland category.
- Results in a 42% increase in average grassland livestock stocking density (scenario including CH_4).

Key changes under S4c

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- A 30% decrease in grassland livestock numbers by 2050.
- 302,000 ha of grassland on organic soils rewetted successfully by 2050 (which is estimated as 90% of that category of current land use).
- 70,000 ha of exploited peatland rewetted successfully by 2050 (which is estimated as 100% of that category of current land use).
- 200,000 ha of additional forestry by 2050 (rate of 8000 ha yr^{-1}) coming from the grassland category.
- Results in a 19% change in average grassland livestock stocking density.

Key changes under S4d

- A 30% decrease in emissions intensity from grassland livestock production by 2050 (cattle and sheep).
- A 30% decrease in grassland livestock numbers by 2050.
- 302,000 ha of grassland on organic soils rewetted successfully by 2050 (which is estimated as 90% of that category of current land use).
- 70,000 ha of exploited peatland rewetted successfully by 2050 (which is estimated as 100% of that category of current land use).
- 500,000 or 875,000 ha of additional forestry by 2050 (planting rate of 20,000 or 35,000 ha yr^{-1}) coming from the grassland category.
- Results in a 0% change in average grassland livestock stocking density (scenario including CH_4).

4.2.5 S5: space for nature

At a global level it is increasingly recognised that biodiversity loss and climate change actions need greater levels of coordination to maximise synergies and minimise negative interactions (Pörtner *et al.*, 2021). Biodiversity conservation was identified as a climate response option with high applicability to Ireland, specifically because many land-based mitigation options, such as large-scale afforestation, can pose a threat to biodiversity (Haughey, 2021). Under this scenario, space for nature is provided by dedicating 10% of the total grassland area in 2018 to non-provisioning ecosystem services (Table 4.1). This scenario is modelled as an addition to the combined S4d scenario outlined above, with commensurate differences in land use change required to free up space.

Key changes under S5

- 420,000 ha of space for nature coming from the grassland category by 2050 (equivalent to 10% of total grassland area in 2018).
- Plus all other measures under S4d.
- Results in a 16% increase in grassland livestock stocking density (scenario including CH_4).
- This scenario is linked with the combination scenario S4d, which includes animal number reduction permutation to ensure that land is available.

4.2.6 S6: space for bioenergy (grassland or perennial crop based)

In terms of its potential to contribute to climate mitigation, bioenergy has been identified as having potentially high applicability to Ireland, albeit with considerable challenges regarding scale-up based on current low levels of deployment (Haughey, 2021). Generally, in an Irish context, there are three main types of bioenergy feedstock sources: annual crops grown on cropland, perennial crops (e.g. miscanthus) or woody perennial species (e.g. willow), and forage from grassland. These distinctions between bioenergy feedstocks and their associated land use are important when considering the suitable land available and have implications for changes to soil carbon stocks that occur during land use change.

Under this scenario 10% of the grassland area circa 2018 is dedicated to providing feedstock for bioenergy (Table 4.1). This 10% area is modelled in addition to S4d and its measures. It is assumed that perennial bioenergy crops (grasses or fast-growing trees) are used, so no significant change in terrestrial carbon storage occurs. Since conversion to permanent rotational cropland does not occur, the soil carbon lost due to initial land conversion over a 20-year period is estimated to be minimal.

Key changes under S6

- 420,000 ha for forage or perennial crops used for bioenergy coming from the grassland category by 2050 (equivalent to 10% of total grassland area in 2018).
- Plus all other measures under S4d.
- Results in a 16% increase in grassland livestock stocking density (scenario including CH_4).
- This scenario is linked with the combination scenario S4d, which includes animal number reduction permutation to ensure that land is available.

4.2.7 S7: space for additional cropland

Ireland currently has a relatively small area of cropland (see Figure 1.1), and the main crops cultivated are not very diverse (Haughey, 2021). This potentially raises concerns regarding national-level food and feed security both at present and in the future, especially considering the projected impact of climate change on global food security (see section 6.1.4). However, any conversion to cropland from other land use categories has implications for GHG fluxes and overall net-zero targets for the AFOLU sector, since conversion to cropland is often associated with soil carbon loss, at least in the short term. Cropland could also be used for the cultivation of bioenergy crops such as oilseed rape for biodiesel or sugar beet for bioethanol production. This would have the potential to positively impact on national climate mitigation targets and reduce dependence on fuel imports. However, there are considerable technological barriers to uptake, including the need for market development. A commonly cited problem with the use of cropland for biofuel production in Ireland is the already limited area under cultivation, with implied threat to feed and food production. Increasing the overall cropland area could alleviate some of that land use demand.

Under this scenario the conversion of grassland to cropland for food, feed or bioenergy crop production was considered[13] (Table 4.1). This was modelled as a conversion of 10% of the total grassland area circa 2018 to annually tilled cropland by 2050. We note that this is a significant simplification in terms of land suitability for cropland, and further investigation would need to include soil characteristics and topography. Since this scenario includes a conversion

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[13] In practice, this option needs to take account of current CAP rules for eligibility for direct payments. Under the 2023–2027 CAP, GAEC standard 1, set out in Annex III to Regulation (EU) 2021/2115 on the CAP Strategic Plan, requires "maintenance of permanent grassland based on a ratio of permanent grassland in relation to agricultural area at national, regional, subregional, group-of-holdings or holding level in comparison to the reference year 2018. Maximum decrease of 5% compared to the reference year."

from grassland to cropland, there are associated soil carbon losses due to cultivation. Soil carbon loss was calculated from this conversion based on IPCC Tier 1 SOC change for high-activity clay soils in a cool, wet climate: (65.55 − 95 Mg C)/20 years = −1.473 Mg C ha^{-1} yr^{-1} (Equation 2.25 from IPCC, 2006).

Key changes under S7

- 420,000 ha for cropland coming from the grassland category by 2050 (equivalent to 10% of total grassland area in 2018).
- Plus all other measures under S4d.
- Results in a 16% increase in average grassland livestock stocking density (scenario including CH_4).
- This scenario is linked with the combination scenario S4d, which includes an animal number reduction permutation to ensure that land is available.

4.3 Scenario Greenhouse Gas Results

Net GWP_{100} balance is critically affected by whether or not CH_4 emissions are included in this balance[14] or dealt with separately. The results will be summarised first without (Table 4.4 and Figure 4.1 upper panel) and then with CH_4 included in the GWP_{100} balance (Table 4.5 and Figure 4.1 lower panel). First, BAU results in AFOLU sector emissions were a very long way off any definition of net zero, ranging from a net emission of 17.3 to 32.1 Mt CO_2 eq depending on whether CH_4 is excluded from or included in the calculation. Overall, irrespective of the treatment of CH_4, the only scenarios that achieve net zero include *all* of the following actions: near-total rewetting of organic soils, aggressive abatement of livestock emissions and ambitious levels of afforestation. Only one of the scenarios achieving net zero does so without also significantly (i.e. by 30%) reducing ruminant animal numbers – and only when CH_4 is excluded from the GWP_{100} balance and new forestry is conifer dominated, reflecting faster rates of carbon sequestration in conifer-dominated than in broadleaf-dominated forestry (Table 4.4).

Key points for CH_4 excluded:

- Even excluding CH_4 from the GWP_{100} balance, neither ambitious afforestation (S1b), nor ambitious rewetting of organic soils (S2), nor agricultural emission abatement combined with ruminant livestock reduction (S3b) can reach net zero on its own (Table 4.4).
- All scenarios involving annual afforestation of 20,000 ha yr^{-1} combined with ambitious organic soil rewetting plus ambitious livestock system emissions decoupling plus significant ruminant livestock reduction (i.e. S4d, S5, S6 and S7) reach net zero.
- S4b, excluding ruminant livestock reduction, also reaches net zero if a conifer-dominant mix of forestry is planted (but fails to achieve net zero with a broadleaf-dominant mix).
- In summary, when CH_4 is excluded from the GWP_{100} balance, the “landing zone” for net zero is much wider, requiring less overall land use change to forestry and covering some land use change from grassland to cropland (S7).

Key points for CH_4 included:

- Only scenarios that include annual afforestation of 35,000 ha yr^{-1} combined with ambitious organic soil rewetting plus ambitious livestock system emissions decoupling plus livestock number reductions (i.e. S4d, S5 and S6) reach net zero (Table 4.5).
- S7, which involves some conversion of grassland to cropland, does not reach net zero.
- Broadleaf-dominated forestry cannot generate sufficient offset to reach net zero in any of the scenarios (unless the planting area is extended further to compensate for the slower rate of biomass production).
- Achieving net zero with CH_4 included in the GWP_{100} balance is very challenging, and almost certainly cannot be achieved without implementing ambitious afforestation rates and peatland restoration as well as an ambitious increase in grassland livestock production efficiency and considerable livestock number reductions.

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[14] The total GHG balance includes CH_4 emissions from agriculture (enteric fermentation and manure management) and LULUCF sources (which includes CH_4 emissions arising from organic soil rewetting). Therefore, in the CH_4-excluded analysis both agriculture and LULUCF CH_4 emissions are excluded from the total GHG balance.

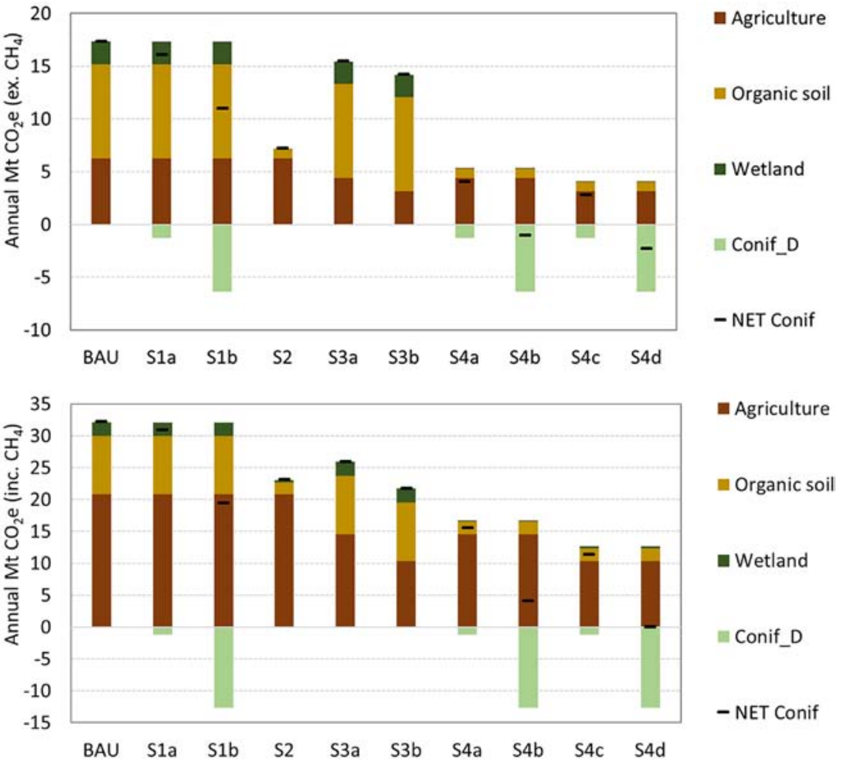

Figure 4.1. GWP$_{100}$ balance (NET Conif) across emissions sources and forestry sink for the main scenarios, excluding (top) and including (bottom) CH$_4$ emissions. Results are presented for the example of conifer-dominated (Conif_D) forestry (70:30 coniferous to broadleaved species split by land area).

- However, despite the challenges, it is still possible to reach net zero and leave scope for the conversion of a significant area of land (420,000 ha by 2050) to perennial bioenergy crops (S6) or to designated space for nature (S5).
- Clearly, in reality, there a myriad of ways in which 420,000 of grassland could be distributed for alternative usage. These will depend greatly on local suitability and wider socioeconomic drivers. However, it should be noted that there are limitations to and potential for feedbacks from land use change and especially soil carbon stocks. For example, due to the impact of tillage, increasing cropland by a modest 10% (S7) means that net zero is not met.

5 Land Use Change Impacts: Synergies and Trade-offs

This chapter examines the potential impacts of the land use changes outlined under the different indicative scenarios on the land system in Ireland. We concentrate mainly on the impacts of the major land use changes that were found to be commensurate with meeting the target of net-zero emissions from the AFOLU sector by 2050. These are large-scale afforestation, agriculture optimisation (increased livestock production efficiency, increases/decreases in livestock density), peatland restoration (restoration/rehabilitation of exploited peatlands, rewetting of grasslands on organic soils) and additional land use options (space for nature, bioenergy from grassland and additional cropland) (Table 5.1). Reports across the IPCC's Sixth Assessment cycle (IPCC, 2018, 2019d, 2022a,b) indicate that urgent action to combat climate change can involve synergies and trade-offs with various other Sustainable Development Goals.

The AFOLU sector in Ireland has the potential to achieve net zero by 2050 (see Table 4.5, S4d), but significant land use change is required (Table 5.1). Depending on the implementation of this land use change, and subsequent land management, mitigation measures in the AFOLU sector could have substantial benefits for biodiversity and water. Conversely, poorly targeted land use change with inappropriate management could have significant trade-offs with biodiversity and water, while also potentially affecting their effectiveness in climate mitigation (IPCC, 2022b). Terrestrial biodiversity loss is intricately linked to how we manage land, while continued biodiversity loss reduces the resilience of ecosystems to climate change extremes (IPBES, 2019). This illustrates that continued biodiversity loss hampers the effectiveness of mitigation in the AFOLU sector and that an evaluation of the trade-offs and synergies of proposed land use changes in the AFOLU sector is essential.

Much of the land use change required to meet net-zero emissions from the AFOLU sector utilises nature-based solutions involving afforestation and peatland restoration, together with livestock optimisation (i.e. making the best use of the available pasture resource; matching livestock numbers to carrying capacity, with improved production efficiencies and reduced environmental impacts). Nature-based solutions to reach net-zero emissions from the AFOLU sector need to concentrate on the maintenance and restoration of carbon sinks to balance GHG emissions, while simultaneously achieving co-benefits for biodiversity, water and human well-being. The success of these land use changes in terms of climate change mitigation is very context specific, and the impacts of these measures on biodiversity and water depend very much on local conditions and land management strategies (IPCC, 2021b).

5.1 Large-scale Afforestation

When deployed using a sustainable land management approach, afforestation can improve water filtration in soil, improve groundwater recharge and reduce soil erosion, run-off and flooding (IPCC, 2019c). Planting forestry with a mix of native tree species is proven to support ecosystem services, biodiversity and air filtration and have social benefits in terms of, for example, cultural heritage, recreation and health (IPCC, 2019c). However, the rapid conversion of thousands of hectares of land in Ireland to forestry could have major environmental impacts on biodiversity and water (Allen and Chapman, 2001; Giller and O'Halloran, 2004; Graham *et al*., 2017; Wilson *et al*., 2012a). Various stages of the forestry management cycle from site preparation and planting to thinning, harvesting and replanting will also have varying levels of impacts on water quality, water quantity and biodiversity. Forest management has a direct impact on the input of carbon into the soil; however, the stabilisation of SOC cannot be influenced by forest management, as this depends on soil properties (Jandl *et al*., 2007). Forest management strategies such as the implementation of best management practices (e.g. buffer, riparian zone management), continuous-cover forestry and close-to-nature silviculture involve less disturbance and exposure of forest floor during the forest cycle and could reduce risks of run-off and soil erosion from rainfall, as well as improving biodiversity outcomes (Jandl *et al*., 2007; Oettel and Lapin, 2021; Shah *et al*., 2022; Sing *et al*., 2018). Overall, the scale

Table 5.1. Overview of major land use changes associated with each modelled scenario by 2050 (including CH_4)

	Afforestation	Agriculture optimisation			Peatland restoration		Additional land use options		
Scenario	Total ha (annual rate ha yr^{-1})	Increase in livestock production efficiency (%)	Change in total ruminants (%)	Change in livestock density (%)	Rewetting grasslands on organic soils (ha)	Exploited peatland restoration (ha)	Space for nature	Bioenergy from grassland	Additional cropland
S1a	200,000 (8000)	0	0	5					
S1b	875,000 (35,000)	0	0	26					
S2	125,000 (5000)	0	0	13	302,000	70,000			
S3a	125,000 (5000)	30	0	3					
S3b	125,000 (5000)	30	–30	–28					
S4a	200,000 (8000)	30	0	16	302,000	70,000			
S4b	875,000 (35,000)	30	0	42	302,000	70,000			
S4c	200,000 (8000)	30	–30	–19	302,000	70,000			
S4d	875,000 (35,000)	30	–30	0	302,000	70,000			
S5	875,000 (35,000)	30	–30	16	302,000	70,000	420,000		
S6	875,000 (35,000)	30	–30	16	302,000	70,000		420,000	
S7	875,000 (35,000)	30	–30	16	302,000	70,000			420,000

and direction of impacts of forestry practices on biodiversity and water are context specific and depend on the existing ecological condition of afforested sites, afforestation practices and ongoing forest management.

Much of Ireland's previous afforestation took place on organic and gley soils, replacing peatland, heathland and wet grassland (semi-natural and semi-improved) ecosystems (Wilson *et al*., 2012a), with a smaller proportion on well-drained mineral soils, replacing semi-improved and improved grassland. Large-scale conversion of open habitats to forestry will have a significant impact on species, with those associated with open areas replaced by species associated with scrub/woodland habitats (Buscardo *et al*., 2008; Graham *et al*., 2013; Wilson *et al*., 2012a). However, in landscapes dominated by improved agricultural grasslands with relatively low levels of scrub/woodland habitats, afforestation is likely to increase bird biodiversity (Wilson *et al*., 2012a). There is some evidence to suggest that the negative ecological impacts of conifers are minimal up to approximately 25–30% cover in lowland farm landscapes and that young forest areas in these landscapes could be beneficial (Wilson *et al*., 2012a). However, the abundance and diversity of bird species in general declines with canopy closure in conifer-dominant plantations. Unplanted areas in forested landscapes and their subsequent management may allow persistence of low-lying shrubs and ground/field layers, mitigating some of the impacts on associated ground-nesting birds (Wilson *et al*., 2012a), but there is increasing evidence that predation risk increases in these situations (Wilson *et al*., 2012b).

The scale of the impact and whether this is positive or negative are largely determined by the species composition of the open habitats the forestry is replacing and the species choice, species mix and management of the afforested area (Graham *et al*., 2017). The type of forestry planted and the vegetation cover it replaces also directly influence biodiversity and ecosystem services (IPCC, 2019c). Biodiversity of birds in Irish plantation forests largely depends on habitat complexity and the diversity of habitat in the forested landscape (Graham *et al*., 2013). Afforestation represents a particular threat to semi-natural habitats with distinctive local plant communities, but afforestation of improved grassland may be of benefit to biodiversity in intensively managed landscapes (Buscardo *et al*., 2008). Configuration and management of open spaces and buffer zones is an important factor in the mitigation of biodiversity and water impacts of an afforestation programme. Species dependent on open habitats and those dependent on shrub layers and near-ground cover are mostly absent in the later stages of the conifer plantation management cycle (closed canopy). These include hen harrier, merlin, red grouse, stonechat, whinchat, curlew, lapwing, grasshopper warbler, reed bunting, whitethroat and willow warbler (Wilson *et al*., 2012a), and many of these are species of conservation concern due to existing habitat loss.

Afforestation, particularly when conifer dominated, exacerbates the acidification of soil and aquatic systems, especially in acid-sensitive catchments (Giller and O'Halloran, 2004; Tierney *et al*., 1998). Biodiversity of freshwater macroinvertebrates can be reduced more at afforested sites than at peatland and semi-natural sites, with negative impacts most evident in areas with > 25% closed canopy (Tierney *et al*., 1998). The management of riparian zones, species mixes and forest management practices in afforested catchment are particularly important in mitigating the impacts of afforestation on water and biodiversity of aquatic systems (Giller and O'Halloran, 2004). Evidence suggests that the resultant impact of afforestation on water, as on biodiversity, appears to be catchment context specific and varies with afforestation practices. The impacts of afforestation on water quality can be positive or negative over time. Increased afforestation can have unintended impacts on water quality, hampering the achievement of EU Water Framework Directive targets, but there is also potential for improved water quality from land use change, particularly where undisturbed forest cover replaces more intensive land use practices (Duffy *et al*., 2020).

As with water quality, the effects of afforestation on water regulation can be negative or positive and are related to a combination of catchment characteristics, afforestation establishment and ongoing management practices. Groundwater recharge or potential contributions to flooding vary at different stages in the forestry management cycle (e.g. reduced infiltration with afforestation; increased infiltration during clear felling (Allen and Chapman, 2001)). Afforestation, if properly situated and well managed, has the potential to alleviate flooding but if poorly managed can lead to increased flood risk and siltation, with the potential for nutrient loss during management events (Allen and Chapman, 2001). Studies in conifer forests have demonstrated that forest cover can be effective in mitigating small and frequent stream flows, but they may have little impact on reducing peak flow in extreme large flood events (Xiao *et al*., 2022).

The existing land cover/habitat type and landscape composition of areas targeted for new plantations clearly influences the environmental outcomes for GHG fluxes, water and biodiversity. It is clear from a biodiversity perspective that afforestation should be targeted at sites of low conservation value and, when planning afforestation in any area, that sites of high nature value should be retained (Graham *et al*., 2017). Many important areas for biodiversity are designated for nature conservation and protected under the Birds and Habitats Directive, but a large proportion of important grassland and peatlands remains unprotected (Wilson *et al*., 2012a). For example, approximately 50% of high nature value farmland occurs outside protected areas (Matin *et al*., 2020; Moran *et al*., 2021). There are clear emerging patterns in the literature of potential co-benefits for biodiversity and water of planting on improved agricultural areas that are relatively intensively managed, but significant trade-offs occur when planting on semi-natural areas of high nature value (Buscardo *et al*., 2008; Graham *et al*., 2017). Afforestation of open habitat of high conservation value will generally have negative impacts on biodiversity. There is potential for significant impacts on areas of high nature value farmland that are farmed at low intensity with relatively high levels of semi-natural vegetation (including of shrub and tree cover). Ecosystem condition is an important factor when assessing the impact of proposed land use change. Degraded sites with little prospect of restoration to their original state may provide opportunities for afforestation with co-benefits for biodiversity and water with appropriate species choice and subsequent management.

5.2 Peatland Restoration

Peatlands are important areas for biodiversity. Intact peatlands provide multiple ecosystem services, including water regulation, erosion and fire prevention, and are among the most important soil carbon stores both in Ireland and globally. However, over 80% of Irish peatland ecosystems have been degraded as a result of peat extraction, agriculture and plantation forestry (Connolly, 2018; NPWS, 2015; Pschenyckyj *et al*., 2021; Renou-Wilson, 2018). Approximately 84% of the remaining natural peatlands are protected under the EU Birds and Habitats Directives (Malone and O'Connell, 2009; NPWS, 2015), forming part of the EU-wide Natura 2000 network of designated nature conservation sites. One of the key benefits of restoring peatlands and organic soils is the potential to reduce carbon losses in a relatively short time following rewetting (Renou-Wilson *et al*., 2019). As well as co-benefits for biodiversity, the restoration of peatlands could have significant co-benefits in terms of improved water quality and water regulation by, in some cases, reducing the costs associated with treating drinking water, improving flood management by reducing peak flows in catchments and contributing to base flow and groundwater recharge during drought conditions (Andersen *et al*., 2017; Bonn *et al*., 2016; Pschenyckyj *et al*., 2021; Renou-Wilson, 2018; Tanneberger *et al*., 2021).

Successful ecological restoration (in terms of creating an active peatland habitat) has the potential to create a long-term carbon sink (IPCC, 2019d). The carbon stored in a functioning peatland offers low risk of carbon saturation and sink reversibility. This is in contrast to a high level of afforestation, which brings with it increased potential for sink reversal when events such as wildfires occur, which are becoming more likely due to climate change (IPCC, 2019c).

It should be noted that where peatland rewetting occurs emissions of CH_4 are likely to increase due to rewetting of drained peatland. However, this is counteracted by the creation of a larger CO_2 sink over time (see section 2.6). What is less certain is the impact of climate change on the functioning of peatlands as well as on successful restoration. Where summer drought events result in temporary lowering of the water table in peatlands, this will likely result in a loss of carbon. Therefore, the frequency and intensity of such events could have significant local impacts on peatlands. This should be taken into account where possible during the design and roll-out of interventions on used and degraded peatlands, future-proofing as much as is practicable against expected climate impacts.

Restoration to a pre-disturbed ecosystem is a major challenge in degraded peatlands, and the degree to which peatland ecosystems can be restored to ecosystems approximating intact peatlands depends on a range of site-specific conditions, including the degree of modification of the peatland (drainage, nutrient status, peat extraction, land use change to agriculture grassland, cropland or forestry) (Renou-Wilson *et al*., 2018, 2019). These studies highlight that natural vegetation can be restored on rewetted bogs on sites where initial drainage was the only disturbance (i.e. no afforestation or peat extraction). Renou-Wilson *et al*. (2018) highlight that the site conditions prior to restoration and the methods utilised strongly influence the restoration outcomes on afforested peatlands and peat extraction, with management decisions often requiring a balancing act between biodiversity and climate benefits. The authors recommend the following prioritisation in the rewetting of degraded peatlands to maximise biodiversity benefits and climate change mitigation potential: rewetting drained-only and domestic cutover areas; rewetting grassland on peatland soils; rewetting industrial cutaway areas; and rewetting afforested peatland areas.

Generally, it is expected that the restoration of wetlands could support livelihoods and help sequester carbon (*medium confidence*), provided that they are allowed accommodation space (IPCC, 2022a). However, there are many barriers to the implementation of successful peatland restoration, including local topographical and hydrological constraints. These could significantly affect the economic cost of interventions required to raise the water table to a sufficient level to reduce emissions and create carbon sinks. Therefore, the highly ambitious rewetting and restoration levels outlined under S2 are likely to be difficult to achieve in practice. Furthermore, care should be taken when planning individual wetland restoration projects that maladaptive responses are avoided and any potential negative impacts from changes in local hydrology are taken into account. There are also strong socioeconomic barriers to implementation, including a loss of income from grassland rewetting or reconversion to peatland for farmers and the potential loss of access to turf for fuel. Peatlands in Ireland are owned by a mix of state and private landowners, with individual sites often under multiple ownership (DAHG, 2015), and restoration activities require coordination with and agreement from landowners. International evidence suggests that a high level of engagement between local communities and the land management and planning process can facilitate the implementation of such land-based conservation measures (Hurlbert *et al*., 2019).

5.3 Agricultural Optimisation

5.3.1 Increasing agricultural efficiency

Increasing the production efficiency of agriculture in Ireland has been assessed as having significant climate mitigation potential (Haughey, 2021). The efficiency measures that could be implemented range from improved genetics for crops, forage plants and livestock and precision agriculture techniques to integrated soil, water and pest management, and many more. The efficiency measures targeted at reducing GHG intensity that are most relevant to the agriculture sector in Ireland comprise three main categories: improved grazing land management, improved livestock management and improved cropland management (Haughey, 2021; Smith *et al*., 2019). Note that this does not include improvements to soil management that aim to increase soil carbon sequestration, which, as outlined in Chapter 2, involves complex interactions between soil type, current carbon content and stock, land management and climate.

Under S3, a 30% reduction in agricultural emissions intensity by 2050 is included. This value was taken as a representing the upper end of the potential for mitigation in agriculture activities based on current technologies. Clearly, given the large role played in Ireland’s agricultural emissions by CH_4 from enteric fermentation, any technology that could achieve significant reductions without negative externalities in terms of input source (e.g. seaweed extract, lipids, 3-NOP) or animal health could change this picture (see section 2.2). Nevertheless, even if such technologies were available, there would be associated costs, and universal uptake would not be likely without some form of subsidisation or clear market incentive.

In terms of impacts, it can be expected that improved efficacy will result in more efficient nutrient use in the system, which would in theory reduce pressure on water quality. Similarly, when implemented on a large scale, options to reduce volatile nitrogen emissions from manure spreading and fertilisers could have benefits for climate mitigation, by reducing N_2O emissions, but also for air quality and biodiversity, by reducing ammonia (Bourdin *et al*., 2014; Lalor and Schulte, 2008). However, expected gains in terms of absolute agriculture GHG emissions reductions through the application of more efficient agricultural practices may be reduced by rebound effects (Mbow *et al*., 2019). In the case of livestock emissions, which play such a significant role in Ireland’s GHG emission profile, there is a particularly strong risk of rebound effects, since livestock numbers on farms can in theory be increased significantly over a few years in response to economic or policy drivers. This therefore represents a risk with regard to reducing absolute emissions from agriculture.

5.3.2 Changes in livestock density

Agricultural activities have complex interactions and effects on biodiversity (Benayas *et al*., 2007). The impact of changes in livestock densities will vary considerably across the country based on a range of site- and catchment-specific factors, including soil type, existing ecosystem state (e.g. low or high biodiversity area), location relative to critical source areas, hydrological susceptibility, current intensity of management and nutrient loading. This section highlights the need for catchment-specific approaches to changes in livestock densities if co-benefits for biodiversity and water are to be realised.

Many of the areas important for biodiversity in Ireland are associated with low-intensity, high nature value farmland (Moran *et al*., 2021), which are dependent on extensive grazing practices. The main pressures on extensive grassland systems in Ireland and across Europe are intensification/abandonment of management and afforestation (Lomba *et al*., 2020). Reduced stocking rate on existing high nature value farmland could result in land abandonment and loss of biodiversity, while increasing stocking densities on the same land could also transform existing semi-natural pasture into semi-improved and improved grassland of lower biodiversity value (Henle *et al*., 2008; Lomba *et al*., 2020). Increased stocking densities require increased production of forage, which is often associated with increased fertilisation and higher frequency of cutting and grazing of the grassland areas, which are the main drivers of grassland biodiversity loss at field scale (Dumont *et al*., 2019; Hopkins and Holz, 2006).

The potential contrasting outcomes from changes in livestock densities are illustrated in a review by Benayas *et al*. (2007). The work highlights that the impact of reduced livestock densities, which may lead to land abandonment in some areas, varies regionally across Europe, and the same is likely in an Irish context. Land abandonment in high nature value areas can lead to biodiversity loss, possibilities of increased fire risk, loss of cultural and aesthetic services (recreation opportunities) and reduction in landscape diversity. Conversely, depending on the context/initial environment condition, the resultant change in land use may be beneficial in terms of natural regeneration of vegetation, reforestation, water regulation, soil recovery, nutrient cycling and increased biodiversity. In semi-improved and improved grassland it must be noted that reduction in stocking density alone does not necessarily lead to an increase in biodiversity but requires targeted management to enhance biodiversity value (Isselstein, 2005; Rook *et al*., 2004).

The EU’s Water Framework Directive seeks to achieve good status in all water bodies, including groundwater, rivers, lakes and estuarine waters (European Commission, 2020c). One of Ireland’s commitments under the Directive is to report water quality status. The primary pressure on water quality in Ireland is the entry of excess nutrients in the form of nitrates and phosphorus to water bodies. The main sources of these nutrients are agricultural run-off and wastewater treatment (EPA, 2019). Increases in the concentration of these nutrients cause excessive plant growth and make algal bloom events more likely. In 2020, nitrate pressure was most severe in groundwater, with 39% of monitored sites having poor to bad nitrate status (EPA, 2021b). Although less significant, nitrates are also a problem in rivers, with 18% of monitoring sites displaying poor to bad status. Worryingly, since 2013 the number of Irish rivers with nitrate levels greater than $11.5\,\mathrm{mg\,L^{-1}}$ has increased by 10% (EPA, 2021c). Since nitrates from agricultural run-off are closely linked to the intensity of land use, there are strong regional dynamics, and, generally, river, groundwater and estuarine water bodies are worst affected in the south-east (EPA, 2021b). A higher level of nutrient inputs from slurry and fertiliser in the south and east is further indicated by a greater number of farms operating under Nitrates Directive derogations in these areas than in the west and north (EPA, 2021b). Such derogations allow higher stocking densities on farms, subject to additional water protection measures being put in place to reduce the risk of nutrient run-off entering waterways.

Owing to different physio-chemical characteristics, the pressure on water quality associated with phosphorus is markedly different from that associated with nitrates. Since 2013 the greatest increases in phosphorus concentrations have occurred in areas with poorly draining soils and more intensive agriculture, indicating that the spatial distribution across the country is more complex than that of nitrates pressures (EPA, 2021b). In 2020, phosphorus pressure on Irish water bodies was most severe in rivers, with 24.5% having poor to bad status (EPA, 2021b). Nevertheless, the quantities of phosphorus and their potential impact on ecosystem function vary by types of water bodies, and lakes are particularly vulnerable to phosphorus, which can severely impact local aquatic ecosystems.

Pollution impact potential maps of phosphorus and nitrogen have been produced for every catchment in the country (https://gis.epa.ie/EPAMaps/) and are a vital resource for assessing the potential impact of changes in stocking densities on water quality. These maps rank the relative risk to water bodies from diffuse phosphorus and nitrogen losses from land, combining information on diffuse sources of nutrients from agriculture and susceptibility of the land to losses. An increase in livestock density is likely to be associated with a decrease in water quality and biodiversity (Coyle *et al*., 2016; Valujeva *et al*., 2016), particularly in areas with high pollution impact potential. Increased forest cover and substitution of livestock, compatible with several of the illustrative scenarios outlined in this report, may have positive impacts on water quality. The combined impact of forest cover and reductions in livestock numbers may result in water quality improvement, but, as highlighted earlier, the appropriate management and siting of afforestation is essential to realising these benefits.

The relationship between land management and intensity and water quality is complex, and catchment and farm characteristics play an important role (Doody *et al*., 2012). The need for catchment-specific approaches has also been identified in high nature value farmland areas with existing extensive livestock systems to realise the co-benefits for water and biodiversity (Moran and Sullivan, 2017). Clearly there is a need for optimisation of management at farm and landscape/catchment scale, which considers diversity in catchment characteristics and farm contexts. A one-size-fits-all approach will not work. When trying to optimise livestock densities to meet climate mitigation targets, a flat rate reduction/increase in densities across the country is very likely to have unintended negative consequences for biodiversity, water and climate mitigation.

5.4 Providing Additional Space for Nature

The space for nature scenario (S5) provides for the allocation of 10% of the total grassland area in 2018 to biodiversity and associated ecosystem services. It must be noted that, in practice, it is likely that the 10% target included in S5 has already been met, as Irish grassland farms already contain more than 10% average semi-natural features, such as hedgerows, field margins, woodland, scrub and wetlands (Larkin *et al*., 2019; Rotchés-Ribalta *et al*., 2021; Sheridan *et al*., 2017). However, because of the resolution of the available land cover data, we cannot account for this situation in S5; higher-resolution land cover data for Ireland are urgently needed (see section 6.3.1) to quantify existing semi-natural features and space for nature on Irish farmland. The retention and enhancement of semi-natural vegetation on farmland benefits biodiversity and associated ecosystem services, depending on type of feature and location, can have additional benefits for water regulation and water quality (García-Feced *et al*., 2015; Rotchés-Ribalta *et al*., 2021). As well as their value for biodiversity, hedgerow, buffer strips, field margins and farm woodlands can play major roles in regulating and supporting production through pollination, pest control and erosion prevention (García-Feced *et al*., 2015).

Recent catchment-level studies indicate that the share of semi-natural areas on Irish farms exceeds 5% of the farm area, with averages ranging from approximately 6% on intensively managed farms to over 40% in extensively managed farmland areas (Rotchés-Ribalta *et al*., 2021). Semi-natural vegetation is dominant in high nature value farmland areas of Ireland (Sullivan *et al*., 2017). These farmland areas are recognised for their importance to biodiversity and multiple ecosystem services such as food and fibre provision, pollination, pest control, water regulation, climate mitigation and cultural and aesthetic services (Lomba *et al.*, 2020). A review of the available evidence on carbon storage and sequestration on semi-natural habitats has been carried out in England (Gregg *et al.*, 2021). The report highlights large variation in carbon storage and sequestration across typical farmland habitats such as woodland, hedgerow, scrub, semi-natural grasslands and heathlands. Carbon storage and flux also vary with habitat condition. For example, taller and wider hedgerows have greater potential for carbon sequestration. Estimated average sequestration for hedgerows in good condition is approximately $2\,t\,CO_2\,eq\,yr^{-1}$ (Gregg *et al.*, 2021), equating to approximately $840\,kt\,CO_2\,eq\,yr^{-1}$ under S5.

Habitat quality across Ireland is highly variable (Rotchés-Ribalta *et al.*, 2021); 85% of habitats monitored under the EU Habitats Directive are currently of unfavourable conservation status, and 46% of these display a declining trend (NPWS, 2019). Habitats and species designated under the EU Habitats Directive must be assessed periodically as part of Ireland's commitments under the legislation. During the most recent reporting period (2013–2018) the most frequently recorded pressures and threats to habitats came from agricultural activities. Among the agricultural activities identified as pressures, the most common was "intensive grazing or overgrazing pressure by livestock", accounting for 55% of habitats affected by agriculture (NPWS, 2019), while in 39% of such habitats "extensive grazing or undergrazing" was cited as the pressure in question, highlighting the often-complex interactions between agricultural management and biodiversity. Many significant non-agricultural pressures and threats on habitats were identified, including alien and problematic species, development and construction, forestry and the extraction of resources (NPWS, 2019).

Separately protected species are also assessed, and the picture of threats and pressures is different from that of those experienced by habitats (NPWS, 2019). Again, a wide range of species are negatively impacted by agricultural and forestry activities, ranging from plants and molluscs to fish and mammals. One reason for these wide-ranging effects of land management on species conservation status is that local-level activities can impact on habitat quality at significant distances from the site of action. This includes activities such as land drainage and associated increased sediment flow, harvesting operations in forestry and nutrient run-off from agricultural land. These pressures are compounded by climate change and are likely to result in increasing pressures in the future. The latest data on the birds of conservation concern in the island of Ireland, compiled by BirdWatch Ireland and the RSPB NI (Gilbert *et al.*, 2021), indicate that in this reporting period 23 species moved into the red list and only six left it. The habitats with the greatest levels of red-listed species are upland and farmland areas, which are predominantly under agricultural use, albeit at varying levels of intensity. In upland areas, the key pressures on bird species are predation, habitat degradation through afforestation, overgrazing by sheep and peatland degradation (Gilbert *et al.*, 2021). The processes of soil erosion in upland areas, especially on peatland, interact strongly with grazing pressures and increasing climate change impacts.

5.5 Using Grassland for Bioenergy

The Sustainable Energy Agency of Ireland (SEAI) has estimated that everyday economic activity in Ireland produces a range of low-value and sustainable biomass resources that could provide about 6.5 TWh of Ireland's fuel, or about 4% of its primary energy supply (SEAI, 2022). Under S6, 10% of the grassland area in 2018 would be used for bioenergy by 2050. This could be in the form of either perennial forage (e.g. *Miscanthus*) or fast-growing woody species (e.g. willow) as bioenergy feedstock. As noted in Chapter 4, this would involve some land preparation and tillage in the initial planting; however, we expect the loss of soil carbon over the lifetime of these perennial crops to be minimal. This is an important distinction between S6 and S7, with the latter seeing change to rotational cropland and not to perennials.

Alternatively, the use of grass forage as feedstock for anaerobic digestion could provide another option for bioenergy from grassland and would likely have much greater synergies with the management of existing improved or intensively managed grasslands. The anaerobic digestion of grass can be used to produce biogas (around 55% CH_4), which can be refined further into biomethane (around 97% CH_4). This is approximately equivalent to natural gas and can provide a renewable source of energy across a wide range of sectors. Using harvested forage from grasslands as feedstock for aerobic digestion is recognised as having a particularly large potential in Ireland due to a combination of the dominance of grassland, favourable climatic conditions, avoidance of soil tillage (and associated carbon loss) as well as the familiarity of farmers with grass production systems (Murphy and Power, 2009). The ability to focus on grass-based feedstock production on marginal grassland is also regarded as having a significant potential to reduce pressures on food production systems as well as providing diversified income streams for regions with lower agricultural production potential.

Meehan *et al*. (2017) investigated the feasibility of using marginal grasslands for biomethane production by comparing yields of different grass species from three marginal grassland sites with those from a more productive site. Two of the three sites showed no significant difference in grass yields and only at a very wet site were there lower grass yields compared with the more productive site. Analysis of the energy system outcomes associated with these results showed that forage from marginal grassland sites on mineral soils could provide sufficient energy for the demands of the heavy goods vehicle and private car fleets in Ireland with minimal impact on food production (Meehan *et al*., 2017).

There is also scope for using grass forage and animal slurry in a co-digestion process, which can enhance the production of biomethane as well as providing a sustainable end-use for animal slurry (Himanshu *et al*., 2018). It has been estimated (based on current livestock forecasts) that biomethane production from a grass silage/slurry mix could deliver 2.7 TWh of biomethane, equivalent to 5% of the current gas supply in Ireland (SEAI, 2022). However, the use of marginal grasslands for biomethane production faces other challenges such as significantly lower forage yields and poor trafficability of soils that have poor drainage. Furthermore, many of the marginal grasslands in Ireland are currently semi-natural grasslands under extensive grazing management. Many of our most threatened habitats and species of international conservation concern are dependent on this high nature value farmland (Moran *et al*., 2021). Increasing the intensity of production on extensive semi-natural grasslands and switching from a grazing to a mowing regime may have negative impacts on biodiversity. This would need to be taken into account in the design of future grassland management systems for feedstocks for anaerobic digestion to minimise potential trade-offs. It should also be noted that recent life cycle assessment analyses indicate that GHG mitigation potential of anaerobic digestion declines as the energy and transport systems decarbonise (Styles *et al*., 2022). The same study finds that anaerobic digestion is relatively inefficient compared with other options. For example, afforestation can mitigate six times more GHG per hectare of land used than grass-biomethane transport fuel.

5.6 Converting Grassland to Cropland

There is potential for significant benefits in terms of national-level food and feed security where more land is used for crop and horticulture production. This is particularly important in the light of current food security pressures globally (DAFM, 2022b). However, cultivation of land currently in the grassland land use category will result in soil carbon losses due to tillage. Implementation of minimum tillage practices could reduce negative impacts on carbon stocks. In practice, implementation will be limited by the availability of suitable land for conversion to tillage, although innovations could be explored, including the development of suitable machinery for soil types not currently cultivated. It is worth noting that, compared with present levels, a much larger area of land was used for crops in Ireland historically (see section 1.1.6). The impact of conversion to cropland on biodiversity and water quality could be positive if best practice implementation of environmental measures occurs, but there is potential for negative impacts (Table 5.2).

Climate change mitigation potential could improve where the additional land is used for annual bioenergy crops, especially if this is implemented along with cultivation practices such as minimum tillage. Where these are applied primarily to cropland, the area available for bioenergy crops is expected to be limited by food and animal requirements. In a life cycle assessment analysis of the impacts of bioenergy crops in Ireland on GHG balances, Clarke *et al*. (2019) found that both the type of bioenergy and the land use change involved were important. Their study examined the cultivation of miscanthus

Table 5.2. Assessment of synergies and trade-offs across the land use change measures included under the set of scenarios considered in this report

Land use change	Mitigation	Adaptation	Biodiversity	Water quality	Notes/comments
Afforestation					
					Forest carbon sinks saturate over time and there is a significant risk of sink reversal due to unsustainable future management or natural disasters (e.g. wildfire). Climate change exacerbates these risks. Afforestation in unsuitable areas (e.g. organic soils) is a concern. The trade-offs and synergies with biodiversity and water depend on the existing ecological condition of the afforested site, species selection and afforestation practices.
Conifer dominated	+++	±	±	±	Afforestation where planting is dominated by non-native conifer species can have a potentially negative impact on biodiversity and water quality, and depends on site-specific characteristics and landscape context.
Broadleaf dominated	++	++	++	+	Afforestation with more slower-growing broadleaved species can have a positive impact on biodiversity and water quality.
Agriculture optimisation					
Increased production efficiency	++	++	=	++	Widely beneficial but could have a net negative impact on mitigation where rebound effects result in increases in absolute emissions.
Increased livestock density on grasslands	=	−	−	−−	Likely to have a negative impact on water quality where the density of grassland livestock is increased. Actions can be taken to reduce negative impacts on water quality (such as removing access of livestock to waterways).
Decreased livestock density on grasslands	=	±	±	+	Likely to have benefits to water quality where density of grassland livestock is reduced; however, this is predicated on appropriate management of livestock (i.e. even at lower density there is potential for adverse outcomes).
Peatland restoration					
					Potential future vulnerability with these benefits/synergies under future climates. Drought periods and higher winter temperatures are likely to increase carbon losses from the systems. There is also a greater risk of wildfire during summer drawdown events, which could lead to significant short-term emissions and impact future ability to assimilate carbon and resilience climatic variability.
Exploited peatlands	+++	+++	+++	+++	Expected to be widely beneficial, noting the vulnerability of the carbon sink in future climate. In addition, there are likely to be site-specific constraints on successful implementation.
Organic soils under grasslands	+++	++	++	++	Expected to be widely beneficial, albeit dependent on the level of land use intensity following rewetting. There is considerable uncertainty with regard to the loss of grassland productivity and impact of rewetting on land management (i.e. trafficability for livestock and machinery).

Table 5.2. Continued

Land use change	Mitigation	Adaptation	Biodiversity	Water quality	Notes/comments
Additional land options					
					Note that to ensure the availability of land to conduct these measures these scenarios were modelled as additions to scenario S4d.
Space for nature (S5)	++	++	+++	+++	Expected to be widely beneficial. There is considerable uncertainty with regard to the loss of grassland productivity. There are likely to be co-benefits for the long-term sustainability of agroecosystem productivity, with positive impacts on nutrient cycling and pollination services.
Bioenergy from grasslands (S6)	++	±	±	±	Significant potential for mitigation benefits by displacing fossil fuels with bioenergy, which is a renewable source, especially in the case of woody perennial species and perennial grasses. However, this is more variable in the case of anaerobic digestion.
Additional croplands (S7)	−−	++	±	±	Cultivation will result in soil carbon losses from soil currently under grasslands. Impact on biodiversity and water quality could be positive if best practice implementation occurs. Where the additional land is used for annual bioenergy crops, the mitigation potential could improve. Implementing carbon mitigation practices such as minimum tillage could also improve the mitigation potential.

The assessment presented in this table is qualitative and based on the expert opinions of the authors.

Table indicator notes

Indicator	Description
+++	Large positive – synergy
++	Moderate positive – synergy
+	Small positive – synergy
=	Neutral or low confidence in direction
−	Small negative – trade-off
−−	Moderate negative
−−−	Large negative
±	Variable – may be positive or negative

(*Miscanthus* × *giganteus*) and short rotation coppicing of willow (*Salix* spp.) on either grassland or cropland. In both bioenergy systems the major drivers of GHG emissions were (1) field operations such as land preparation and harvesting as well as the production of syntenic fertiliser, and (2) the loss of soil carbon due to cultivation. Emissions associated with field operations were reduced through the substitution of synthetic fertiliser with organic sources. Importantly, this study found that conversion of cropland to miscanthus and willow were net GHG sinks and the conversion of pasture to miscanthus was close to GHG neutral, but the conversion of grassland to willow was a significant net GHG source (Clarke *et al*., 2019). This finding indicates challenges for large-scale roll-out of these bioenergy crops in Ireland due to the limited cropland area and the likelihood that significant conversion of cropland to bioenergy would impact on food security and result in “off-shoring” of food production, which could lead to an increase in GHG emissions elsewhere.

5.7 Integrated Land Use Planning and Optimisation

This report highlights the large-scale land use change that would be required to meet net-zero AFOLU emissions targets by 2050. Land management options targeted at climate action, including afforestation and bioenergy crops, can pose unintentional threats to biodiversity and water quality, particularly where they are deployed as monocultures covering large areas (IPCC, 2019d). The development of other infrastructure aimed at climate mitigation such as solar or wind farms could also create threats to biodiversity conservation when located in nature conservation areas or high nature value farmland habitats. Where agriculture and forest areas coincide with existing important areas for biodiversity, there may be significant barriers to, and trade-offs associated with, land use change, exacerbated by conflicting land use objectives associate with different energy, food, biodiversity, water and climate policies.

Given the broad range of land use objectives, it is essential to develop an overall integrative approach to land management and land use planning. An integrated land use approach aims to target land use to meet multiple goals cognisant of the trade-offs and synergies between them while balancing environment, social and economic outcomes. This requires strategic targeting of land use that acknowledges the varying capacity of different land types to provide a diverse range of ecosystem services from provisioning (e.g. food and fibre), regulating (e.g. climate, water) and supporting (e.g. nutrient cycling) to cultural (aesthetic, recreation) services. The approach would support policymakers, land managers and users in selecting the appropriate land use strategies to meet the needs of society while protecting natural resources and ensuring the continued supply of ecosystem services from functioning ecosystems in good condition.

The Irish landscape encompasses a wide range of land types characterised by differences in geology, topography, soils, climate and land cover (Carlier *et al*., 2021). These land types range from intensified lowlands to extensive mountainous areas and have a wide range of land use capacities. Different land types are made up of different combinations of ecosystems of varying extent and condition, and, as a result, land types function differently and each is predisposed to provide a particular set of ecosystem services. The landscape variation requires regional and local adaptation of national policy targets, similar to the integrated catchment management approach to the implementation of the Water Framework Directive and the locally adapted agri-environmental scheme approach as exemplified by the Burren programme (Murray, 2020). The participation of local communities in the decision-making process facilitates the transparent development of effective solutions, and engagement between local communities and landowners with a more holistic land management and planning process is essential to overcome resistance to sustainable land management programmes (Hurlbert *et al*., 2019; Murray, 2020). Local participatory approaches are recognised as essential components of integrated catchment management and locally adapted agri-environment schemes in Ireland.

Scenario modelling makes it clear that achieving the net-zero target for the AFOLU sector requires substantial reconfiguration of land use across Ireland in the coming decades. The success of this reconfiguration will need to be measured in terms of its contribution to mitigating and adapting to climate change; ensuring just transition across society; minimising trade-offs and synergies with other ecosystem services; and also ensuring that the reconfiguration does not exacerbate other global society challenges (e.g. biodiversity loss, food and water security). This will require an integrated land use strategy coordinated by a whole-government approach, while ensuring buy-in from and participation by the whole of society. Table 5.2 provides a high-level qualitative analysis of the synergies and trade-offs between land use change and other key environmental indicators. Many of the land use changes, which are compatible with net-zero targets for the AFOLU sector, provide considerable co-benefits across environmental indicators and so represent areas where actions could take place in the near term. However, for other actions significant trade-offs have been identified, and careful planning and implementation is required to minimise negative impacts. It should be noted again that an analysis of socioeconomic impacts was beyond the scope of this work, but some important interactions have been noted in Table 5.2.

In an unmanaged land use change transition, the individual choices for intensification, expansion and drainage are neither based on nor optimised for knowledge about soil type, soil properties, soil nutrient levels or soil carbon contents. Land use change could have significant negative impacts if implemented unsustainably and, if left unguided, this could inadvertently lead to the expansion of forestry onto vulnerable soils or into high nature value grassland, or to drainage of high carbon soils. To achieve the levels of land use change outlined in this report while minimising negative externalities, an overall integrated land use management strategy for the country is needed. In contrast to the unmanaged scenario, a managed land use transition would ensure that pathways are customised for the properties of individual fields, soils or catchments (Valujeva *et al.*, 2016). However, in practice implementing these actions requires them to be scaled down to a level that facilitates local adaptation within the national framework. In the example of afforestation, this would require national coordination regarding overall targets across various environmental and societal objectives, as well as coordination at an appropriate regional or community level to implement and manage forests sustainably. There is little question that the restoration of forests in Ireland could have many positive environmental impacts, but the potential negative impacts cannot be ignored (Allen and Chapman, 2001). There is reason to believe that catchment-level effects are more important in explaining the relationships between plantation forests and the water and biodiversity of aquatic systems, highlighting a clear need for integrated catchment management (Giller and O’Halloran, 2004). A similar argument could be made for catchment-scale implementation in relation to optimised livestock management including guidance on appropriate livestock densities.

Targeting land use for both afforestation and bioenergy in Ireland is complex and challenging. There have been calls to target these land-based mitigation options at so-called “marginal grassland” soils[15] (Farrelly and Gallagher, 2015). The area of “marginal grassland” has been estimated at 1.3 million hectares, which could therefore provide significant land-based mitigation. In theory, this targeting of bioenergy crops and afforestation would prevent production losses from more productive grasslands and croplands and subsequently support sustainable food and feed production. In this case, marginal refers to lower potential for agricultural productivity because of soil type or other geophysical constraints such as slope or aspect. However, the focus on marginal grassland for climate action in Ireland poses specific challenges for sustainability, the environment and society. Marginal agricultural land is not distributed evenly across the country, and such land is found predominantly in the border, west, mid-west and midland regions. Focusing afforestation on these areas would result in significant changes to the landscape, with the potential to impact on sectors beyond agriculture, including tourism and cultural heritage. Much of this farmland identified as marginal from a food production perspective as a result of natural constraints is also identified as high nature value farmland. The distribution of marginal grassland soils coincides with the distribution of high nature value farmland (Matin *et al.*, 2020), which is limited in terms of food provision services but is associated with clean water, high biodiversity, high soil carbon storage and aesthetic and recreation services (Gardi *et al.*, 2016; Moan and Sullivan, 2017; Moran *et al.*, 2021). Finally, the soil type used for afforestation or bioenergy would need to be carefully

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[15] Here, marginal refers to lower potential for agricultural productivity due to soil type or other geophysical constraints such as slope or aspect.

considered, as planting on organic soils (including marginal grasslands on former peatlands) could result in significant unintended carbon losses. Climate action and land use strategies that do not take an integrated and more holistic approach to initiate sustainable land management run the risk of significantly exacerbating the biodiversity crisis, deteriorating water quality and reducing the resilience of ecosystems to climate change.

6 Options to Support Policy Development

This chapter provides a high-level analysis of the current policy landscape with regard to land use and management. In section 6.1 a comparison is made between current policy targets for land use change and those set out under the indicative land use change scenarios developed in Chapter 4. In section 6.2 the potential for climate mitigation in the AFOLU sector is summarised for the options considered under the indicative land use change scenarios. Finally, in section 6.3 important knowledge gaps and key uncertainties regarding supporting policymaking for sustainable land use in Ireland are summarised.

While this chapter provides an overview of some of the key policy documents concerning land use and the AFOLU sector in Ireland, the list of documents considered is by no means exhaustive. The general approach was to include the most recent and relevant outputs, although it should be noted that the implementation time frames across the various documents are not harmonised. There are three main categories of organisations responsible for these policy statements: (1) EU level, such as the European Commission, (2) Irish Government department level, such as the Department of Agriculture, Food and the Marine (DAFM) or the Department of the Environment, Climate and Communications, and (3) state or semi-state agencies, such as the OPW, or Bórd na Móna.

This is a complex policy landscape, and often the same government department or organisation has multiple policy documents concerning land use. This is due to the ways in which land use and land-based activities are divided between various legislative frameworks and objectives. For example, there are in many cases separate policy documents addressing climate change and biodiversity or water quality targets. While a detailed mapping exercise was beyond the scope of this report, some of the key policy documents and their targets are summarised in Table 6.1.[16] Overarching many of the individual policy documents is the Government's 2021 Climate Action Plan (DECC, 2021). It is of note that the Government's Climate Action Plan is implemented by each relevant sector. This plan is included in the analysis, but we have also included recent policy documents from individual departments and bodies. In some cases, the 2021 Climate Action Plan may include updated targets from those in individual sectoral policy documents.

6.1 Alignment Between Current Policy Landscape and Land Use Change Scenarios

The scenarios outlined in Chapter 4 of this report include large changes in land use at the national level targeted at achieving net-zero emissions from the AFOLU sector by 2050. Here an analysis of how these changes match targets or stated objectives in relevant policy documents is undertaken. The analysis is not exhaustive in terms of the policy documents reviewed and focuses only on the changes required under the scenarios outlined in Chapter 4.

6.1.1 Afforestation targets

This is one of the areas in which the current targets for land use change diverge most from those identified in the indicative scenarios in Chapter 4. Current policy in Ireland is relatively consistent, with a target of 8000 $\mathrm{ha\,yr^{-1}}$ across multiple policy documents (Table 6.1). Yet this level of afforestation falls short of the rates compatible with net-zero targets by mid-century (based on the indicative scenarios developed in this report), which are between 20,000 and 35,000 $\mathrm{ha\,yr^{-1}}$ depending on whether or not CH_4 is included in net-zero targets. We note that some of the policy targets assessed include objectives relating to increased use of timber biomass in HWP and energy generation, which could help offset emissions from the energy or construction sectors. However, this was not included in this report's scenario analyses (see section 4.2.1).

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[16] For a detailed analysis of the policy sphere regarding land use in Ireland, see the policy catalogue also conducted as part of the Land Use Review (Minogue Environmental Consulting Ltd, 2023).

Table 6.1. Summary of interactions between current policy targets and the land use changes required to meet the net-zero target by 2050 as outlined in the scenarios developed in Chapter 4 of this report

Land use changes	Relevant scenarios	Relevant policy documents/strategies
Afforestation	**S1, S4, S5, S6, S7**	
875,000 ha of additional forestry by 2050 (rate of 35,000 ha yr^{-1}) coming from grassland category	S1b	**EU Forest Strategy:** All managed public forests and a larger number of private forests should have forest management plans. **EU Biodiversity Strategy 2030:** Aims to plant an additional 3 billion trees by 2030. **Forests, Products and People – Ireland's Forest Policy (2014)**: Targeted increasing afforestation rates to 15,000 ha yr^{-1} as a key policy objective. This report also notes that the 1996 Growing for the Future forestry strategy had an afforestation target of 25,000 ha yr^{-1} by the year 2000. **Climate Action Plan 2021:** A commitment to promote afforestation to increase planting to a rate consistent with realising 2030 ambitions and contribute to achieving carbon neutrality no later than 2050 (no specific afforestation rate specified). Also commits to doubling the biomass supply as a fossil fuel substitute – coming largely from forests. **Food Vision 2030:** A rate of 8000 hectares (minimum) of afforestation per annum. **Ag Climatise:** • Double biomass production from forests (sustainable production). • Increase afforestation to 8000 ha per year. • Displace 2 Mt CO$_2$-eq in GHG by forest-based biomass not suitable for HWPs. **National Development Plan 2021–2030**: Afforestation target of 8000 ha per year. Note that the National Development Plan is closely linked to the national policy commitments in the Project Ireland 2040 – National Planning Framework.
Peatland restoration	**S2, S4, S5, S6, S7**	
302,000 ha of grassland on organic soils rewetted successfully (which is estimated as 90% of that category of current land use)	S2	**Climate Action Plan 2021:** A commitment to reduced management intensity (water table management) of 80,000 ha on drained organic soils by 2030. **Ag Climatise:** Reduce management intensity of 40,000 ha of peatlands. Not clear about specific impact on water table levels or total GHG flux. **Food Vision 2030:** Under Action 4, Carbon Farming, there is a commitment to maintenance of current soil carbon stocks and "plugging of hotspots in organic soils". **NPWS National Peatlands Strategy:** Document refers to these areas as "farmed peatland". Actions include considering support for farmers who are limited in their land management by the EU Habitats Directive.
70,000 ha of exploited peatland rewetted successfully (which is estimated as 100% of that category of current land use)	S2	**Climate Action Plan 2021:** A commitment to rehabilitating 65,000 ha of peatlands across "numerous landowners and projects". **National Development Plan 2021–2030:** The National Development Plan includes the rehabilitation of 33,000 ha of Bord na Móna peatlands. **Bord na Móna Sustainability 2030 Report:** 2020 target to reduce emissions by 75% from 2007 figures. **Our Rural Future 2021–2025:** €108 million state funding assigned to the Bord na Móna "Enhanced Decommissioning, Rehabilitation and Restoration Scheme" to repurpose 80,000 ha of bog. **NPWS National Peatlands Strategy:** Focus on actions to stop carbon loss in both designated (for conservation) and non-designated sites. Section 4.3.2 states that the National Raised Bog SAC Management Plan will provide for the restoration of raised bogs on SACs (special areas of conservation).
Agriculture optimisation	**S3, S4, S5, S6, S7**	
A 30% increase in grassland livestock production efficiency	S3a	**Climate Action Plan 2021:** Commitment to a 22–30% reduction in agriculture emissions by 2030 (note that this goes beyond grassland agriculture, which is the focus of the scenario analysis). Various specific actions mention improved agricultural efficiency. For example, Action 311 seeks to introduce measures to promote improved efficiency in livestock. Others mention feed additives targeted at reducing methane from enteric fermentation.

Table 6.1. Continued

Land use changes	Relevant scenarios	Relevant policy documents/strategies
		Ag Climatise: • Reduce overall chemical nitrogen fertiliser use and adopt low emission fertiliser formulations. • Genotype the entire national herd for the development of enhanced dairy and beef cattle breeding programmes – aim to reduce GHG. • Increase milk recording in dairying from 50% to 90%. • Increase beef weight recording from 30% to 70%. • Improve grassland management and grass utilisation. • Improve animal health. **Food Vision 2030**: 10% reduction in livestock CH_4 emissions.
A 30% decrease in grassland livestock numbers	S3a, S3b	No specific mentions of reducing ruminant livestock numbers in the assessed policy documents. **Climate Action Plan 2021:** Action 315 mentions reductions in the slaughter of “prime animals from 27 to 24 months by 2030” (but this is targeted at increased production efficiency, not total livestock numbers *per se*). **Ag Climatise**: Notes that any increase in CH_4 emissions due to increased livestock numbers will jeopardise the sector attaining carbon neutrality by 2050.
Space for nature	**S5**	
420,000 ha space for nature coming from grassland by 2050 (equivalent to 10% of total grassland area in 2018)		**EU Forest Strategy 2030**: There is a “space for nature” target of 30% of EU land area, of which 10% of will be under strict legal protection. **Climate Action Plan 2021:** Action 322 commits to the promotion of ecosystem restoration and conservation through Payment for Ecosystem Services and investment in actions that increase carbon sinks while promoting biodiversity, e.g. woodlands, bogs, soil management, hedgerows. Many mentions of the need to coordinate across sectors on biodiversity including the need to avoid negative impacts through for example inappropriate afforestation. **Draft Summary of Common Agricultural Policy:** • GAEC 1: maintenance of permanent grassland (managed at national level). • GAEC 8: minimum of 4% arable land for non-productive areas, including fallow land. • GAEC 9: ban on converting or ploughing permanent grassland in Natura 2000 sites. **Food Vision 2030:** 10% of farmed land prioritised for biodiversity.
Bioenergy from grassland	**S6**	
420,000 ha bioenergy from grassland by 2050 (equivalent to 10% of total grassland area in 2018)		**EU Forest Strategy 2030:** Currently, 60% of EU renewable energy use is wood-based bioenergy. The EU Forest Strategy aims to increase the share of renewable sources to reach the EU’s 2030 target of reducing CO_2 emissions by 55%. **Climate Action Plan 2021:** Action 318 commits to conducting further research on biomass and manure feedstocks for anaerobic digestion. No specific uptake targets. **Ag Climatise:** • Reduce agricultural energy use by 20%. • Achieve at least 20% deployment of renewable energy technologies (focus on energy-intensive farms). • Work to maximise potential for anaerobic digestion for the agriculture sector. **National Energy and Climate Plan (2021–2030):** Aims to support efforts to increase indigenous renewable sources in the energy mix, including bioenergy. Support the production of bioenergy through the common agricultural policy and the National Policy Statement on the Bioeconomy. **Support Scheme for Renewable Heat (SEAI):** Objectives include an increase in the energy generated from renewable sources in the heat sector. This includes support for the use of biomass-based or anaerobic digestion-based heating systems.

Table 6.1. Continued

Land use changes	Relevant scenarios	Relevant policy documents/strategies
Additional cropland	**S7**	
420,000 ha cropland from grassland by 2050 (equivalent to 10% of total grassland area in 2018)		**Climate Action Plan 2021:** Specific focus is on changes in cropland management to increase mitigation potential of cropland soils (use of cover crops to, and incorporation of straw) and measures to reduce GHGs, e.g. the use of legumes to fix nitrogen in crop systems. **Ag Climatise:** • Increase tillage area to above 300,000 ha (current level). • Enhance the development of sustainable land management practices by delivering 26.8 Mt CO_2-eq abatement through LULUCF. • Increase the proportion of Irish grown protein in livestock rations. • Adopt minimum tillage to conserve soil carbon. **Draft summary of CAP:** GAEC 7: crop rotation in arable land except for crops grown underwater. GAEC 9: ban on converting or ploughing permanent grassland in Natura 2000 sites. Of note in the context of conversion of grassland to cropland.

With regard to definitions of terms used in the various policy document to describe actions or targets, refer to the original policy documents, as the use of terms may not be harmonised.

NPWS, National Parks & Wildlife Service.

A publicly funded afforestation programme will be provided for after the current forestry programme (2014–2020) under the National Development Plan (2021–2030). A detailed new Forest Strategy 2023–2027 for Ireland and an associated Implementation Plan are under preparation by DAFM. At the European level, currently 60% of EU renewable energy use is wood-based bioenergy. The EU Forestry Strategy aims to increase the share of renewable sources in order to reach the EU's target of reducing CO_2 emissions by 55% by 2030 (European Commission, 2021b). Furthermore, the EU Biodiversity Strategy 2030 aims to plant an additional 3 billion trees by 2030. The programme also requires that all managed public forests and a larger number of private forests have forest management plans.

6.1.2 *Wetland/peatland restoration targets*

The peatland restoration targets outlined in policy documents were less coherent than the afforestation targets. This may well reflect fewer available data on the extent and suitability for restoration of degraded peatlands. Targets for exploited peatlands range from 33,000 to 80,000 ha, which encompasses (albeit at the upper end) the 70,000 ha target identified under S2 (which forms part of subsequent scenarios S4, S5, S6 and S7). According to Bord na Móna, its Raised Bog Restoration Programme has successfully restored 7273 ha of bog to peat-forming conditions to date (Bord na Móna, 2022).

The other component of S2 is the restoration of organic soils under grassland, for which the target is 302,000 ha. This is much higher than the current policy target of "reduced management intensity" and/or "water table management" of between 80,000 and 40,000 ha of such grasslands by 2030 (Table 6.1). It is also not clear to what extent the "reduced management intensity" or "water table management" will result in restoration of these former peatlands to peat-forming conditions and to what extent the GHG flux will be impacted (see section 2.6). Under the Ag Climatise plan there is a commitment to identify and determine the drainage status of organic soils under grassland, as well as the development of pilot projects to provide "proof of concept" with regard to rewetting (DAFM, 2020). The planned collection of data and practical trialling of restoration methods is hugely important in the context of the large area to which such measures could be applied and their role in the GHG balance of the AFOLU sector in Ireland.

6.1.3 *Agriculture optimisation targets*

Improving the efficiency of agricultural production and so lowering the emissions intensity associated per unit of food output is a central target of many actions under the Ag Climatise plan (DAFM, 2020). This includes actions aimed at reducing chemical nitrogen inputs through improved nutrient management as well advancing reductions in GHG emissions by optimising chemical fertiliser formulations. Other actions are targeted at improving the efficiency of beef and dairy cattle through animal genotyping coupled with the extensive collection of animal performance data, which can be used to further enhance breeding programmes (Table 6.1). Other measures focus on grassland management and investments in research centred on reducing the level of CH_4 generated during enteric fermentation.

The Ag Climatise plan seeks the development of a "climate neutral food system compatible with the Paris temperature goals, whereby the climate impact of biogenic methane is reduced to zero and remaining agricultural emissions are balanced by removals through land use and a significant contribution to renewable energy" (DAFM, 2020). While there is an overall commitment to "reduce GHG emissions from the sector", the Ag Climatise plan does not state how much each individual action will be expected to deliver. The Climate Action Plan 2021 commits to an overall 22–30% reduction in agricultural emissions by 2030 (note in the context of that report agriculture is dealt separately to LULUCF), with many separate actions targeted at optimisation (Table 6.1). However, the contributions of individual actions to the overall 22–30% reduction target is not detailed (DECC, 2021). This policy analysis did not find any specific targets in relation to reductions in ruminant livestock numbers. The Food Vision 2030 plan specifies a target of a 10% reduction in agricultural CH_4 emissions compared with 2018 by 2030. It is not clear if this would be delivered solely through increased efficiency. However, the Ag Climatise plan and Food Vision 2030 recognise that any increase in CH_4 emissions due to increased livestock numbers could impact chances of achieving net-zero targets by 2050.

6.1.4 Additional land use targets (nature, bioenergy, cropland)

Of all the actions included in the set of scenarios developed in Chapter 4, the target of 10% space for nature is most closely in agreement with key national and EU policies (Table 6.1). Food Vision 2030 specifies a target of 10% of farmed land being "prioritised for biodiversity", and Ag Climatise mentions increased biodiversity as a key objective across several actions (DAFM, 2020, 2021b). At the European level there is a "space for nature" target of 30% of EU land area, of which 10% will be under strict legal protection (European Commission, 2021b). Although the modelled scenario S5 takes the 10% "space for nature" area from the grassland category, in reality this could be divided across all farming operations, including tillage.

Several of the policy documents concerned with bioenergy are, understandably, focused on the energy system and uptake of renewables as opposed to feedstock supply (Table 6.1). The EU Forestry Strategy aims to increase the share of renewable sources to reach the EU's target of reducing GHG emissions by 55% by 2030 (European Commission, 2021b). In Ireland, Ag Climatise has a stated target of displacing GHGs of 2 Mt CO_2-eq with the use of forest-derived biomass not suitable for other uses (DAFM, 2020). However, these targets do not align with the type of non-forestry bioenergy included in S6 of this report. The measures therein focus on bioenergy from grassland forage or manure as feedstock for anaerobic digestion or perennial crops on grassland such as short coppice willow or *Miscanthus*. Ag Climatise has an objective of undertaking work "to maximise potential for anaerobic digestion for the agriculture sector"; however, there are no specific area-based targets. The need for substantial work recognises the challenges of upscaling such measures nationally.

With regard to increasing the area of cropland in Ireland, there are no clear targets. Under the CAP and cross-compliance regulations' Good Agricultural and Environmental Conditions (GAECs), there are some restrictions on the tilling of permanent grassland. This could therefore be a barrier to uptake in some cases (see section 4.2.7). Separately there is a commitment to increase tillage production above 300,000 ha by 2030 with "more native grown grains and legumes for livestock" (DAFM, 2020) (Table 6.1). It is noteworthy that, under the same set of actions, adoption of minimum tillage practices to consider soil carbon is also encouraged.

The Russian invasion of Ukraine in February 2022 and the significant impact of this on wheat trade and subsequent impacts on wheat production in this "breadbasket" region has caused a spike in cereal prices globally. Analysis by the Organisation for Economic Co-operation and Development (OECD) suggests that the full loss of Ukraine's capacity to export wheat combined with a 50% reduction in Russian wheat exports could lead to a 34% increase in international wheat prices in the marketing year 2022/23 (OECD, 2022b). Aside from wheat, Ukraine is the world's largest producer of sunflower seed and a key exporter of rapeseed, barley, vegetable oil and maize (OECD, 2022b). Impacts on global food security have been further compounded by severe weather events in many parts of the world as well as spikes in chemical fertiliser prices. Partly because of these circumstances, there has been significant renewed interest in increasing the area of land under tillage in Ireland. On 30 March 2022, DAFM launched the Tillage Incentive Scheme, which was targeted at increasing the planting of tillage crops in 2022 to reduce dependency on imported feed material (DAFM, 2022b). This measure is in line with the scenario outlined in Chapter 4; we note that the 420,000 ha increase in cropland area is modelled as occurring by 2050.

6.2 Potential for Climate Action in the AFOLU Sector

Globally AFOLU accounted for 22% of total net anthropogenic GHG emissions in 2019 (IPCC, 2022b). Despite being an overall major source of GHG emissions, the AFOLU sector also has substantial potential to mitigate climate change while also supporting biodiversity and the provisioning of ecosystem services (IPCC, 2019c). However, it is important to note that agricultural activities and associated land use and land use change (as part of LULUCF) are dealt with separately according to current GHG reporting conventions under the UNFCCC (see the opening paragraph of Chapter 2). Globally, the total estimated technical mitigation potential of agriculture-related[17] AFOLU sectors is 25.5 (7.6–56.7) Gt CO_2 eq (OECD, 2022a). However, the majority of that mitigation potential lies in land use and agricultural soils, which account for 19.6 (4.9–46.4) Gt CO_2 eq, with much lower potential from direct agricultural activities (OECD, 2022a). Yet affecting change to agricultural practices, including land management, faces significant barriers, including the need for knowledge transfer (see section 6.3.2) and the potential costs of new technologies and alternative practices. Nevertheless, actions for climate mitigation taken in the AFOLU sector have been identified as offering relatively low-cost potential (per USD/T of CO_2 equivalent) compared with other sectors (Wreford *et al*., 2010).

6.2.1 Agricultural activities and land use

As explored in detail in Chapter 2, the agricultural activities and related land use are overall a significant source of GHG emissions in Ireland (see Figure 2.2). This section deals with AFOLU in combination, and, again, it should be noted that much of the mitigation potential lies in land use and not only in changes to direct agricultural activities. Identifying mitigation measures along with a sector-specific emissions budget is a logical economic response to climate change. In Ireland, the 2019 Teagasc marginal abatement cost curve (MACC) analysis provides a detailed basis for this in terms of measures that can be taken, their cost and their potential contribution to mitigation (Lanigan *et al*., 2019). However, this requires some form of linkage with overall sectoral and national GHG emission targets. Sectoral emissions budgets can be used along with voluntary or market-based approaches to provide incentives for their uptake in the agricultural sector (Wreford *et al*., 2010).

Better integration of livestock farming with crop systems could lead to more diversified farm enterprises and improve sustainability and circularity with regard to nutrient cycling on individual farms (Khalil and Osborne, 2022). Agricultural system diversification can also support increased farm resilience to both climate and economic shocks. Examples of such agricultural system redesign include implementation of alternative farming systems such as organic farming, agroforestry or intercropping (Haughey *et al*., 2019). However, there are significant barriers, including the need for investment in new farming systems, a lack of enabling conditions in terms of access to or development of new markets, and restrictive agricultural policies (Hurlbert *et al*., 2019). In Ireland, research has shown that farmers'

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[17] This is the total excluding the subcategory "other AFOLU non-relevant for agriculture".

perspectives on alternative systems also present a significant challenge. Meredith *et al*. (2015) found that, when asked about preferred farm development plans, more farmers said that they generally preferred further specialisation (of their current main form of agriculture) to diversification. More research addressing the barriers to uptake of alternatives is needed, as is additional engagement with stakeholders regarding the wider benefits of diversification, such as increasing resilience to extreme climate events.

Preventing land use change from grassland and forestry to cropland is recognised as a measure that can maintain carbon stocks and potentially increase carbon sinks in agriculture (FAO, 2020a). The Green Direct Payment to farmers under the EU CAP is an example of an important policy for retaining permanent grassland, which has associated environmental benefits for soil quality, carbon sequestration and biodiversity (FAO, 2020a). Regulation 2018/841/EU binds GHG emissions and removals from land use, land use change and forests in the 2030 climate and energy framework. This regulation rewards countries that increase carbon sequestration in soils and vegetation in the land sector, which includes agriculture. While increasing soil carbon sequestration in agricultural systems has been a key goal for EU countries, European agricultural policy has thus far been somewhat limited in effecting positive change in terms of soil carbon sequestration (Verschuuren, 2018).

There are opportunities for carbon sequestration via restoring degraded soils, improving crop yields and protecting and planting additional hedgerows. Sustainable grassland management practices such as using optimal stocking rates (avoiding heavy grazing) to minimise leaching, soil erosion and poaching can mitigate the amount of carbon lost within grassland systems (Eze *et al*., 2018). There is also an important difference in how carbon is stored under different management types. For example, in extensive grassland, more carbon is stored in soil as litter instead of being exported from the system as forage (Chang *et al*., 2016). However, practices to implement soil carbon sequestration measures need to be adapted to local soil conditions and land management options (Amelung *et al*., 2020). Clear policy signals to the agricultural sector are essential to enable farmers to make investment decisions that facilitate their transition to low-carbon agriculture, particularly in farming systems with high investment costs (OECD, 2019).

6.2.2 Forest and woodland

Land management options such as increased afforestation have a large potential to contribute to climate change mitigation goals, and as they are established practices they could be deployed in the near term (Lanigan *et al*., 2018; McGeever *et al*., 2019). However, there are significant barriers to afforestation, including a reluctance among landowners to convert agricultural land to forestry. For example, Lanigan *et al*. (2018) identified an afforestation rate of 7000 $ha^{-1} yr^{-1}$ as an achievable target for Ireland, which is lower than the current government targets and well below some of the targets outlined in afforestation scenarios considered in this report (Table 6.1).

Sustainable forest management requires a balance between actions targeted at the production of wood products, with those targeted at other services provided by forest ecosystems. As in the case of agricultural intensification, there are challenges associated with ensuring afforestation is sustainable where it is deployed in a purely commercially focused manner. Forest management focused solely on increasing biomass stocks may have negative impacts on the resilience of the forest system in the face of climate change or natural disasters and negatively impacts biodiversity. Yet sustainable forest management can achieve significant co-benefits for biodiversity conservation, reducing land degradation pressures and enable improved water and flood regulation (Olsson *et al*., 2019; Smith *et al*., 2019).

In Ireland, there is considerable scope to further diversify the number of forestry species grown, identify alternative management options such as continuous cover forestry and seek a balance between commercial goals and broader ecosystem and cultural services. Across the EU, there has also been an increasing trend of non-wood product-related employment in the forestry sector, primarily as a result of tourism and recreational activities (Simpson *et al*., 2008). The objectives of forest land use as part of landscape-based recreation are different from conventional commercial goals and therefore warrant inclusion in forest planning and governance (Lazdinis *et al*., 2019). There are likely to be some negative cost implications associated with implementing sustainable forest management practices. However, the economic costs should be weighed against large potential co-benefits for climate change adaptation, biodiversity conservation and water management and quality. Coillte currently manages 20% of its estate (approx. 90,000 ha) with “nature conservation and biodiversity as the primary objective” (Coillte, 2020).

A report by the FAO (2022) outlines the potential of HWPs to replace other materials as they are recyclable and often more biodegradable than other materials and provide continued carbon storage during their lifetime. However, potential risks are associated with increasing the production and use of forest products, such as unsustainable forestry practices targeted solely at maximising production without taking wider ecosystem services and biodiversity into account (FAO, 2022; Verkerk *et al.*, 2020). The IPCC (2022b) report also highlights the potential for using long-lived HWPs and better recycling of HWPs as valid methods of storing carbon in wood products. There is recognition that wood products used to store carbon would have to be produced sustainably, including sustainable forest planning and management (FAO, 2022; IPCC, 2022b). We note that it was not possible to include HWPs as part of the GHG analysis related to scenarios in Chapter 4. Further research to allow such an analysis to be conducted is recommended.

6.2.3 Wetland/peatland

To optimise climate resilience, networks of large, protected areas that include all types of habitats and ecosystems are more favourable than small and dispersed protected areas. This is reflected in the Global Deal for Nature proposal that calls for the expansion of protected land area networks (Carroll and Noss, 2021). However, the effective management, restoration and protection of peatlands is required at both local and regional levels (Moomaw *et al.*, 2018). At the ecosystem scale, vegetation composition on peatlands depends on water level, nutrient availability and pH (Limpens *et al.*, 2008). At landscape level, carbon loss to water and the atmosphere is influenced by the land cover percentage of peatlands and the connectivity of those peatlands to other ecosystems (Limpens *et al.*, 2008).

As noted in Chapter 5, there is substantial potential to halt the loss of carbon from degraded peatlands in Ireland through rewetting and, where restoration is ecologically successful, create long-term carbon sinks. However, this process will require significant planning, and considerable investment will be needed to carry out and maintain the required infrastructure. One of the key challenges, especially in the context of grasslands on organic soils, is a detailed mapping of their current drainage status. Since much of the major drainage conduced for land reclamation by the state occurred in the middle of the last century, there is much uncertainty about the current functioning of this drainage network. This is important because drainage ditches will become blocked over time if they are not routinely cleared, and so the level of water saturation, critical to soil mineralisation processes, will be affected.

When mapping peatlands in terms of emissions and carbon losses, including hydrological connectivity is important as this can help determine if the effects of drainage have extended spatially (FAO, 2022). Connolly (2018) sets out an overview of what would be required for an integrated wetland GHG emissions and removals monitoring programme in Ireland: (1) the refinement of estimates of spatial extent of peatlands; (2) fine-scale mapping of all peatland areas; (3) the development of a network of *in situ* GHG monitoring infrastructure; and (4) the development of models to upscale peatland GHG data at a national level. Such a programme would enable much greater support for policy development, which is not currently possible.

Another important aspect of peatland restoration in Ireland is the short-term versus long-term effects on GHG balances. For example, where an area of peatland has been converted to forestry it is known that the carbon sequestered in forest biomass is very likely being outstripped by carbon losses from the soil underneath (see section 2.9). Therefore, in terms of ongoing management there are important decisions to be made with regard to the future use of this substantial area, estimated at 300,000 ha of afforested peatlands nationally (Black *et al*., 2009). Restoration of these areas would require removal of forestry and subsequent rewetting, the feasibility of which would necessitate a site-by-site assessment. This would also amount to a deforestation event and so would reduce the area of forest land and have a negative short-term impact on the national GHG inventory for LULUCF. Devaney *et al*. (2017) identified over 3000 deforestation events in Ireland over the period 2000–2012, which constituted around 5457 ha of deforested land. In these deforestation events the principal land use changes were from forest to settlement and from forest to grassland. The same study also found that a significant proportion of deforestation was related to peatland restoration activities. However, successful restoration of the currently afforested peatland soil could stop soil carbon emissions and, over the longer term, create substantial and sustainable carbon sinks. Furthermore, proceeding with peatland restoration sooner rather than later prevents further degradation of the habitat and increases resilience of the ecosystem to climate change (Glenk *et al*., 2021). Avoiding this "mitigation debt" ultimately results in a greater capacity for GHG mitigation and carbon storage in peatlands (Glenk *et al*., 2021).

6.2.4 Bioenergy

Under the 2019 Teagasc GHG MACC analysis, a range of bioenergy options for Ireland were assessed, and these are summarised in Table 6.2 (see Lanigan *et al*. (2019)). Combining the seven options considered (which include those based on biomass, anaerobic digestion and biofuels) has the potential to provide mitigation of 1.733 Mt CO_2-eq yr^{-1}. Most of this potential is provided through the increased use of wood biomass for electricity or heat generation. This would increase the use of waste timber in sawmills as well as the use of harvested roundwood for energy. Note that a significant increase in the use of roundwood for energy may reduce the potential for long-term carbon storage in HWPs. The use of willow biomass as feedstock for electricity generation in stations that

Table 6.2. Summary of bioenergy mitigation options adapted from the 2019 Teagasc GHG MACC analysis for Ireland (Lanigan *et al*., 2019)

Bioenergy type	Option specification	Energy type or target use	Mitigation potential (Mt CO_2 eq yr^{-1})	Context/caveats
Biomass (compatible with S6)	Wood biomass (harvested wood fuel and sawmill waste)	Electricity/heat production	0.759	Based on increased use of sawmill waste and roundwood for energy generation. Roundwood for energy generation was assumed to be 21% of the total by 2030. Increased use of timber in this way could reduce potential for long-term carbon storage in HWPs.
	Willow (short rotation coppice)/*Miscanthus*	Heat production	0.179	Use of willow or *Miscanthus* biomass as a renewable heating source could reduce the use of fossil fuels. Assumed that 15,000 ha of willow and *Miscanthus* was cultivated on grassland replacing low-intensity beef farming.
	Willow (short rotation coppice)	Electricity production	0.196	This option could be used to provide feedstock for currently peat-fired energy generation stations. Assumed willow yield of 10 tonnes dry matter ha^{-1} yr^{-1} on 9000 ha on converted grassland replacing beef farming.
Anaerobic digestion (compatible with S6)	Forage and slurry (grassland)	Combined heat and power	0.224	Generation of biogas or biomethane for use in combined heat and power plants offsetting fossil fuel derived energy. Significant initial costs in infrastructure required.
	Forage and slurry (grassland)	Biomethane – as a natural gas substitute	0.150	Biomethane could be injected into the existing gas grid infrastructure for range of uses. Significant initial costs in processing infrastructure required.
Biofuel crops (compatible with S7)	Oilseed rape	Biodiesel	0.174	Biodiesel could partially offset imports of fossil fuel. Assumed that a realistic output would be 10,000 tonnes yr^{-1}. Significant initial costs in processing infrastructure required.
	Sugar beet bioethanol	Bioethanol	0.051	Bioethanol could offset some fossil fuel imported. Assumed here that 20,300 ha planted by 2030. Significant initial costs in processing infrastructure required.

Options are grouped here based on type of bioenergy system, with relevance to the scenarios developed in this report indicated.

currently use peat could significantly reduce costs of infrastructure. In the MACC analysis use of willow and miscanthus for biomass production is focused on grassland and specifically low-intensity beef farming. This would likely maximise potential for co-benefits in terms of livelihood diversification on farms, where implemented at appropriate scales and integrated with current agricultural production systems. However, it should be noted that increasing the use of biomass as an energy source poses significant problems for air quality, especially where deployed at large scales (Tomlin, 2021). Therefore, potential negative impacts on air quality should be taken into account in the planning of additional use of biomass in the energy system.

The combined mitigation potential of anaerobic digestion to produce biogas/biomethane for use in combined heat and power plants and biomethane as a substitute for natural gas have been estimated at $0.374\,\mathrm{Mt\,CO_2\,eq\,yr^{-1}}$ (Table 6.2). Similar to biomass as a replacement for peat in energy generation, the use of biomethane as a natural gas substitute has an associated reduced base investment as it would make use of existing infrastructure. However, there would still be considerable costs associated with setting up anaerobic digestion facilities and processing biogas to produce biomethane.

Two biofuel options were also considered as part of the 2019 Teagasc MACC analysis: oilseed rape for biodiesel and sugar beet for bioethanol (Lanigan *et al.*, 2019). The analysis indicated that these biofuel options were most likely to contribute to fossil fuel displacement (Table 6.2). Since these biofuel options use annually cultivated crops on permanent cropland, they are compatible with S7 as outlined in Chapter 4. As noted previously, without the conversion of additional grassland to cropland the competition for that limited cropland resource may intensify in Ireland.

6.3 Knowledge Gaps and Key Uncertainties

6.3.1 Spatial land use and land cover data

At present, Ireland does not have a dedicated land use database system, which makes an analysis of both current and historic land use challenging. More data are available for land cover, such as the CORINE Land Cover Inventory, which provides a pan-European land cover map. However, land cover maps generally categorise land in terms of broad classes that are derived from satellite imagery, while land use refers to the sum of activities and inputs applied to individual parcels of land. Satellite-sourced land cover data can provide highly useful information but deliver only a relatively crude assessment of land use and are particularly limited in providing information on land use intensity. This is problematic since land use data are used for the estimation of many GHG fluxes from the land system in Ireland (Haughey, 2021). Currently, many of these estimates are based on national-level data, which may omit regional and land use-specific dimensions. However, work has been under way since 2011 to improve the availability of land use data, including the potential of using existing field-scale datasets (Zimmermann and Stout, 2020). A new land cover dataset is currently being developed by Ordnance Survey Ireland and the EPA and is expected to be delivered in 2022. This new land cover dataset will form part of Ordnance Survey Ireland's national map spatial framework and provide a spatial database mapping all land parcel boundaries, buildings, roads, pathways and water bodies in the country (EPA, 2021a).

Improving the mapping of land use and land cover in Ireland will provide greater resolution and allow clearer links between land cover and GHG emissions. This should assist in the development of methods by which spatial land use planning could be deployed in the future. One of the key challenges in using land cover data in any environmental analysis is appropriate application of the classification system used. For example, in the CORINE dataset pastures are part of the agriculture land cover class and natural grassland in the forest and seminatural class. It is not immediately clear how semi-natural grasslands fit into this categorisation. Indeed, it may not be possible to infer this solely from satellite data. Schmit *et al.* (2006) found that general-purpose land cover maps such as CORINE strongly overestimated arable land use and were not able to infer minor land use classes accurately. The authors concluded that if finer-resolution land use data were required it would be more appropriate to aggregate using fine resolution spatial data, explicitly taking patterns of land use into account. There is wide variation within land cover classes in soil type and land management intensity.

This is particularly evident in the pasture category, as suggested by the analysis of Gardi *et al*. (2016).

6.3.2 Knowledge sharing for co-creation of solutions

All AFOLU sectors will need to develop, coordinate and implement sustainable management practices to effectively contribute to mitigating climate change (Altieri *et al*., 2015). Disseminating farmers' agroecological practices, documenting the effectiveness of these practices, and transferring this knowledge to other members of the farming and scientific community via cross-visits, courses, seminars and farm visits are all methods suggested to increase awareness of climate change strategies. These knowledge exchange activities could be used to demonstrate the management activities that can improve the resilience of individual farms in the face of extreme weather events such as drought. There are also direct links between the resilience of rural communities to external stresses, be they environmental, political or social, and their ability to increase the resilience of agroecosystems on their land. This can be supported by the effective transfer and exchange of knowledge across the agricultural community (Altieri *et al*., 2015). The sustainable and/or agroecological practices already in place on farms along with social networks in the community are factors that can determine the extent to which individual farms or farming groups respond and adapt to climate change events (e.g. extreme weather events) (Altieri *et al*., 2015).

The importance of knowledge sharing to successful outcomes has been recognised in the context of sustainable intensification of agriculture and may be applied to either high- or low-tech activities, the central tenet being that more sustainable farming practices are often more knowledge-intensive (Haughey *et al*., 2019). Where agricultural system redesign is the objective, knowledge transfer and agricultural extension services play a particularly critical role (Pretty and Bharucha, 2018). For example, increasing the uptake of more diverse farming systems such as agroforestry or organics often requires alternative and integrated pest and nutrient management.

Practical on-farm demonstration of sustainable farming systems has been shown to strengthen knowledge transfer outcomes (Šťastná *et al*., 2019). However, across Europe the distribution of such on-farm demonstration methods is not equally divided between farming systems, with organic farms more highly represented. Furthermore, topics covered by such demonstrations focus disproportionally on technological solutions and less on topics relating to broader farm business management, which are important in the context of overall sustainability (Šťastná *et al*., 2019). In Ireland under the Ag Climatise plan there is a commitment to establish a network of "sign-post farms" for the demonstration of actions targeted at sustainable climate adaptation and mitigation (DAFM, 2020). This is a very positive development and recognises the importance of knowledge transfer in the roll-out of climate actions in the agriculture sector.

A BAU approach to disaster risk management in the agricultural sector is not an option if global food production and sustainable agricultural growth are to continue (OECD, 2021). Three key recommendations for stakeholders in preparing for natural disasters and implementing strategies to reduce the impact on agriculture are (1) provide targeted direct payments, risk management tools and access to advisory services to help farmers prepare for, mitigate and prevent the impacts of natural disasters; (2) focus policy investment towards developing a resilience toolkit for farmers (e.g. target training and extension services, availability of targeted, science-based information about risk management and adaptation, supporting nature-based solutions on farms); and (3) engage with trusted stakeholders to motivate farm-level change – all farm groups should have access to new research/support (OECD, 2021). This should be done by policymakers engaging with trusted stakeholders in the agricultural sector such as co-ops and advisory groups (OECD, 2021).

Olesen *et al*. (2011) conducted questionnaires with agroclimate and agronomy experts across 26 countries to gather their anticipated risks and impacts of climate change on agriculture in Europe. Methods by which farmers are already adapting to climate change include selecting alternative crop cultivars/species and changing cultivation and harvesting times. Overall, survey respondents perceived grassland to be the least affected of five crops by climate change, with consideration given to hail frequency, heat stress, soil erosion, leaching of nitrogen and weed occurrence (Olesen *et al*., 2011).

6.3.3 Impact of climate variability and extreme events on ecosystem functioning

There is considerable uncertainty regarding the impact of climate change on the functioning of managed and natural ecosystems. While there will be “greening” due to CO_2 fertilisation and longer growing seasons in Ireland, it is not clear what the cumulative impact of climate change will be from an increase in extreme events such as heavy precipitation or droughts and heatwaves. Quantification of this uncertainty is important to allow for the development of adaptation plans for both managed and natural ecosystems.

There is *high confidence* that water cycle variability and related extreme events will increase faster than changes to mean climate conditions in most regions of the world and across all climate change scenarios (IPCC, 2021a). With regard to precipitation patterns, there is evidence that global interannual rainfall regimes have already become more extreme but with smaller changes in mean annual rainfall amounts (New *et al*., 2001; Singh *et al*., 2013). However, most experimental or observational studies of climate impacts on ecosystem function have focused on changes in mean climate variables (Thornton *et al*., 2014) and not for example on increased variability (Jentsch *et al*., 2007; Kayler *et al*., 2015). This is especially important for Ireland since significant changes to the frequency and severity of extreme precipitation events have been projected by mid-century (see section 3.1.3). A controlled environment study has indicated that a more variable water supply without changes to mean levels can negatively impact the shoot-and-root biomass production of monocultures and mixtures of agronomic grassland plant species (Haughey *et al*., 2020). Further work investigating the effects of increased climate variability on the functioning of grasslands and other managed and semi-natural ecosystems in Ireland is recommended.

There are also risks to carbon stocks and sinks from potential future changes in land management (IPCC, 2019d). One of the key risks in relying heavily on land-based climate change mitigation options is sink reversal in the future due to a change in land management such as deforestation or drainage of organic soils. This is further compounded by climate change, which acts as a risk multiplier for carbon stocks in soils and biomass. While many of the climate risks are driven by global trends in GHG emissions and thus rely on global efforts, there are opportunities to ensure that land management options undertaken in the short term take into account, as far as is possible, the impacts of future climate. This type of active adaptation strategy is vital in ensuring that land-based carbon stocks are resilient.

For example, an increase in the occurrence of wildfires could jeopardise carbon stocks in woody biomass, or drought events could cause peatlands to become vulnerable to carbon loss due to decreases in soil moisture. According to the European Forest Fire Information System of the European Commission, the average area of land burnt in Ireland between 2010 and 2019 was 4605 ha yr^{-1} (EFFIS, 2020). Based on the projected change for climate in Ireland, the threat of wildfire is likely to increase in the future. At a 2.0°C global mean surface temperature increase relative to pre-industrial levels the risk to human and natural systems associated with wildfire damage is high (IPCC, 2019d). Importantly, this finding was associated with a rapid increase in risk levels between current warming and 2.0°C above pre-industrial levels. However, many actions can be taken in the near terms to reduce risk, which is especially important in the context of large increases in the area afforested land in Ireland. Options include prescribed or controlled burning to reduce the quantity of fuel in high-risk areas or the introduction of fire breaks in forestry. Resilience of forest ecosystems to wildfire can also be increased using more fire- and drought- resistant tree species (Loudermilk *et al*., 2017). Further work is needed to ensure such land management planning options are explored and where possible embedded.

6.3.4 Water quality and quantity under future climate

Historical relationships between climate and freshwater ecology cannot be assumed to remain unchanged under future environmental conditions due to climate change (John *et al*., 2020). Substantial human adaptation to climate change with regard to water resource management is required, including water transfer schemes, new/improved reservoirs, change in selection of crop varieties to better suit longer growing seasons and warmer air temperatures (Stockmann *et al*., 2013). Longer crop-growing seasons could result in higher chemical inputs, which could increase run-off and leaching of chemicals into freshwater ecosystems (FAO, 2011; Stockmann *et al*., 2013). An unsustainable application of inorganic fertilisers to increase agricultural crop yields contributes to freshwater pollution from run-off and drainage of agricultural land (FAO, 2011). Other land use factors affecting changes in freshwater ecology include agricultural expansion and change in land use, deforestation, grazing density due to run-off and soil erosion. The FAO reports that $2250\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ of effluent is released into the environment, with over half of this attributed to drainage from agriculture (FAO, 2011).

Under its National Water Resources Management Plan, Irish Water has analysed the sustainability of water services in Ireland for the next 25-year period (Irish Water, 2021). A detailed analysis of the projected impact of climate change on the water available for use under future climate conditions was conducted, and the results indicate a substantial decrease in available water by 2044 (Irish Water, 2021). An analysis of the impact of climate change on water demand was also conducted as part of this management plan. However, we note that the factors applied for climate change impacts on water use are currently based on data from the UK as there are insufficient data available for Ireland. The report does not include an analysis of potential increases in the water used for irrigation in agricultural systems. However, as part of the "use less" measures targeted at sustainable water use, it is recommended that when potable water is in short supply grey water is utilised for irrigation (Irish Water, 2021).

6.3.5 Infrastructure and urbanisation

Globally, the urban land area is predicted to triple by 2050, with direct loss of agricultural and forested lands resulting in the loss of soil carbon (IPCC, 2022b). Urban expansion has been identified as a threat to food security (IPCC, 2019d), potentially amplifying risks to the food system from climate change and other stressors. The continued growth of urban areas and associated land use change is expected to place particular pressure on cropland (OECD, 2019). This is important in the context of the Irish land system since there is a high overlap between current cropland cover, driven by soil suitability in many cases, and infrastructure cover (Table 1.1).

Once land is converted to infrastructure, there are very limited options for reconversion to cropland should there be a food or feed security threat. This contrasts with, for example, conversion to grassland, which can be reversed. Trade-offs from the competition for land through economic and market forces can disadvantage smaller farmers. Competition for land may also contribute directly to land use targets not being reached in relation to climate mitigation (IPCC, 2019c). It is important that the development of infrastructure and trends in urbanisation are included as part of overall integrated land management approaches. Where possible, the potential of the land to deliver other provisioning (e.g. soil suitable for tillage) or non-provisioning (e.g. land already providing space for nature) services should be considered alongside its development potential.

6.3.6 Climate services provided by semi-natural land

There is considerable uncertainty regarding the current and future potential contribution of areas of semi-natural vegetation, across a range of habitat and soil types, to climate migration and adaptation goals in Ireland. This is in some contrast to the relatively detailed data available regarding the important contribution such areas make to biodiversity conservation and other ecosystem services such as pollination and water regulation and storage. The lack of quantitative data on carbon stocks, carbon removals and potential for future carbon sequestration severely limits the inclusion of these semi-natural habitats in GHG inventories, and so these habitats are likely to be currently undervalued in the policy framework.

A primary example in Ireland is the potential of and challenge posed by hedgerows in agricultural land. Due to a lack of data and appropriate methods by which hedgerow carbon storage can be assessed, it is not possible to include this in GHG inventories (EPA, 2022a). This is unfortunate since high-quality hedgerows are estimated to contribute to carbon storage (Gregg *et al*., 2021); however, assessing their quality at field scale remains a major challenge. High-resolution land use mapping can also increase the capacity to include nuances in the landscape with regard to carbon storage, taking the example of the potential contribution of extensively managed agricultural land to store SOC (Gardi *et al*., 2016). Urgently addressing this knowledge and data gap is particularly important in the context of setting aside significant areas of land for nature as outlined in S5 (and in many policy documents; see Table 6.1). Being able to quantitatively incorporate the contribution such land makes to climate change mitigation represents a significant opportunity to enhance synergies across land use policies.

6.3.7 Terrestrial carbon and greenhouse gas flux observation systems

The development of coordinated and standardised observational networks for *in situ* measurements of carbon and GHG exchange between terrestrial ecosystem and the atmosphere is important to fully capture the role of key land cover classes in climate warming or cooling, and to better understand the processes driving rates of carbon uptake and GHG release and how these might change in relation to management or climatic variability (Franz *et al*., 2018). In Ireland, there have been a number of short-term (3- to 5-year) funded studies that have assessed the source sink strength of particular ecosystems in terms of carbon uptake and GHG release, and some of these sites have made an active contribution to wider European (CarboEurope, IMECC, GHG Europe and RINGO) or global (Fluxnet) networks. There is however a real need to develop a coordinated national network covering relevant land use, soil type and climate iterations and operating at long-term (decadal) timescales to fully assess the role of land use on carbon assimilation and storage, and to provide the data required for the development of appropriate EFs.

However, the knowledge gaps about the dynamics of terrestrial carbon uptake and GHG release are being addressed through the development and implementation of key observational networks and sites. The most extensive of these is the National Agricultural Soil Carbon Observatory for Ireland (NASCO) led by Teagasc, which has/will deploy > 20 eddy covariance towers to develop verifiable rates of carbon sequestration in grassland and tillage systems across a range of management intensity, soil types and climates. Additional experimental sites are also operational across other key land cover classes such as peatlands and forests, supported by investment in infrastructure from Bord na Móna and the National Parks and Wildlife Service, as well as competitive research funding from the EPA, DAFM, and Science Foundation Ireland. These sites will further our understanding by capturing the impacts of peatland rehabilitation and rewetting and forest type, age, management interventions and climate on the dynamics of carbon uptake and GHG release. There is, however, a real need to secure the long-term operation of all of these sites to ensure that data products are available to develop/refine Irish-specific emission and land management carbon sequestration factors, to support the development and validation of modelling activities and to allow greater spatial upscaling of this information through integration with Earth observation data. This will then provide a platform for developing robust land use decision tools that can inform the development of a national land use strategy.

Furthermore, the recent announcement that Ireland will join the Integrated Carbon Observation System (ICOS) will support this work further. A number of grassland, forest and peatland sites from the national network will be nominated to join the ICOS ecosystem network and thematic centre and will directly contribute to the pan-European network of long-term flux sites.

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Abbreviations

AFOLU	Agriculture, forestry and other land use
AR5	Fifth assessment report of the Intergovernmental Panel on Climate Change
BAU	Business-as-usual
CMIP6	Coupled Model Intercomparison Project Phase 6
CO_2eq	Carbon dioxide equivalent
CSO	Central Statistics Office
DAFM	Department of Agriculture, Food and the Marine
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GWP	Global warming potential
GWP_{100}	Global warming potential effect over 100 years
HWP	Harvested wood product
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land use change and forestry
MACC	Marginal abatement cost curve
NFI	National Forest Inventory
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Co-operation and Development
OPW	Office of Public Works
RCM	Regional climate model
RCP	Representative concentration pathway
SOC	Soil organic carbon
SRCCL	IPCC Special Report on Climate Change and Land
SSP	Shared socioeconomic pathway
tC	Tonnes of carbon
UNFCCC	United Nations Framework Convention on Climate Change

Appendix 1 Supplementary Data

Table A1.1. Land classification and extracted areal extent data (in hectares)

Land class	Code	CORINE sub-land cover class	Total area (ha)	Proportion of total area (%)
Grassland	321	Natural grassland	49,175	0.71
	231	Pastures	3,919,426	56.75
		Sub-total	*3,968,601*	*57.46*
Cropland	211	Arable land (non-irrigated)	320,819	4.64
Other agricultural land	242	Complex cultivation patterns	58,422	0.85
	243	Agriculture with areas of natural vegetation	489,496	7.09
	222	Orchards (fruit trees and berry production)	295	<0.00
		Sub-total	*54,8212*	*7.93*
Forest and woodland	311	Broadleaved forest	53,846	0.78
	312	Coniferous forest	328,671	4.76
	313	Mixed forest	75,882	1.10
	324	Transitional woodland scrub	217,830	3.15
		Sub-total	*676,229*	*9.79*
Peatland and wetland	411	Inland marshes	24,753	0.36
	412	Peatland	975,087	14.12
		Sub-total	*999,840*	*14.48*
Other natural land	322	Moors and heaths	126,668	1.83
	331	Beaches, dunes, and sand	12,108	0.18
	332	Bare rock	19,431	0.28
	333	Sparsely vegetated areas	56,013	0.81
	334	Burnt areas	7932	0.11
		Sub-total	*222,152*	*3.22*
Infrastructure	111	Continuous urban fabric	3753	0.05
	112	Discontinuous urban fabric	107,008	1.55
	121	Industrial or commercial units	14,484	0.21
	122 124	Road, rail, port and airport and associated lands	10,038	0.15
	131 133	Mineral extraction sites, dumps, construction sites	11,360	0.16
	141 142	Green urban areas and sport and leisure facilities	23,676	0.34
		Sub-total	*170,318*	*2.47*
Total land area			6,906,171	–

The land cover categories are based on the categorisation used in this report using CORINE 2018 land cover data. Codes shown correspond to the CORINE database.

Table A1.2. Breakdown of land cover categories as a proportion of the total area of each region (using the NUTS3 classification)

	Land cover category as a proportion of region area (%)							
Region	Infrastructure	Cropland	Other agricultural land	Grassland	Forest and woodland	Other natural land	Wetland (including peatland)	Total area of region ('000 ha)
Border	1.4	0.4	15.8	44.9	10.2	4.6	22.7	1123.3
Mid-east and Dublin	8.9	16.7	4.2	54.8	7.8	3.2	4.4	777.1
Midlands	1.7	3.9	4.6	69.4	10.2	0.1	10.1	652.9
Mid-west	1.8	2.0	6.5	70.4	11.9	2.0	5.4	1009.1
South-east	2.3	13.5	3.7	68.6	8.5	1.4	2.0	714
South-west	2.0	3.5	8.0	56.1	10.3	5.8	14.3	1211.2
West	1.1	0.1	8.5	49.3	9.1	3.0	28.9	1370.4

Total area in '000s of hectares is also shown. Other agricultural land includes complex cultivation patterns, agriculture with areas of natural vegetation, orchards and fruit production. Other natural land includes moors and heaths, beaches, rock, sparsely vegetated areas and burnt areas. Infrastructure includes urban fabric, industrial areas, transport, recreational areas. See Table A1.1 for area breakdown by category.

Table A1.3. The distribution of farm types in 2020 across NUTS3 regions of Ireland

				Farm distribution by specialisation (%)				
NUTS3 region	Tillage	Dairying	Beef production	Sheep	Mixed grazing	Mixed crops and livestock	Mixed field crops	Other
Border	2.7	9.2	19.6	35.5	22.4	5.9	15.8	27.8
West	1.7	5.2	26.5	28.7	30.2	3.6	20.5	10.1
Mid-west	7.2	22.2	16.9	2.5	8.2	8.1	13.8	10.8
South-east	30.3	15.8	6.1	5.7	8.5	33.5	11.8	13.9
South-west	17.5	33.6	13.2	14.3	12.2	13.2	18.5	17.1
Mid-east and Dublin	31.0	6.7	6.6	10.0	11.2	19.2	11.1	12.3
Midland	9.6	7.4	11.2	3.2	7.1	16.5	8.4	7.9

Data source: CSO (2020).

Table A1.4. Sheep population distribution across NUTS3 regions of Ireland in 2021

NUTS3 region	Total sheep	% of total
Border	982,896	24.4
Dublin and mid-east	607,605	15.1
Midlands	255,658	6.4
Mid-west	180,391	4.5
South-east	396,797	9.9
South-west	512,771	12.7
West	1,088,609	27.0
Total	4,024,727	

Data source: DAFM (2021d).

Appendix 2 Literature Search Methodology for Climate Change Impacts on Ecosystem Functioning

The following terms were searched using Boolean search terms using ISI Web of Science, FAO publications library, OECD iLibrary and IPCC search engine: “climate change”, “impact”, “cropland abandonment”, “drought”, “extreme weather event”, “precipitation”, “rainfall frequency”, “rainfall intensity” and “temperature increase”. These search terms were applied in various combinations to six different land uses/habitats: cropland, grassland, forest/woodland, peatlands, freshwater and technogenic/artificial surfaces. The literature search was limited to English-language studies, with no limitation on publication date. Each potential study was initially assessed by title to decide its suitability, then by abstract to determine its relevance to our research and lastly by main text to extract the most relevant information.

In the case where the search returned a very large amount of literature, the results were sorted to list the most cited and/or most recent and used research first. In Web of Science the “sort by” filter used was “citations: highest first” to identify key papers, and then “usage (last 180 days): most first” to identify more recently published and cited key papers. Following this, a filter to show only “review articles” was selected to further narrow the results. In the OECD iLibrary, “article” was selected under “content type”. When searching the OECD iLibrary and the FAO publications library, literature results were sorted by “relevance”.

For some land use types such as “technogenic/artificial surfaces”, key words relevant to our research, such as “land use change”, “land use conversion”, “soil sealing” and “urban”, were also included in the literature search. This made the literature results more suitable to the scope of this review and was necessary to ensure the inclusion of relevant information.

A second search was used for each combination and land use type, filtering results by Ireland-specific literature or research outputs. For Web of Science, “Republic of Ireland” was selected from the “countries/regions” filter, and for FAO publications library and OECD iLibrary “Ireland” was selected from the “country” filter.

A summary of literature search results is provided in Table A2.1. It should be noted that this review was not strictly systematic and was extended to include all relevant research outputs that were known to the research team. For example, where a relevant source known to the research team was not picked up as part of the systematic searches, it was still included in the analysis. This was done since the primary objective here was a comprehensive analysis.

Table A2.1. Total number of returns from literature search for each land use type across database search engines

Land use type	Web of Science	OECD	IPCC	FAO	Total
Cropland	80,564	13,119	9	64,990	158,682
Grassland	854,687	16,097	3	25,178	895,965
Forest/woodland	321,968	52,127	92	80,320	454,507
Freshwater	615,849	80,096	88	95,028	791,061
Peatland	64,005	5400	0	3832	73,237
Technogenic/artificial surfaces	43,653	14,668	0	28,331	86,652

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

Evidence Synthesis Report: 3

Land Use Review: Fluxes, Scenarios and Capacity

Authors:

Eamon Haughey, David Styles,
Matthew Saunders, Ruth Bennett
Coady and James Moran

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

EPA Research Webpages
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