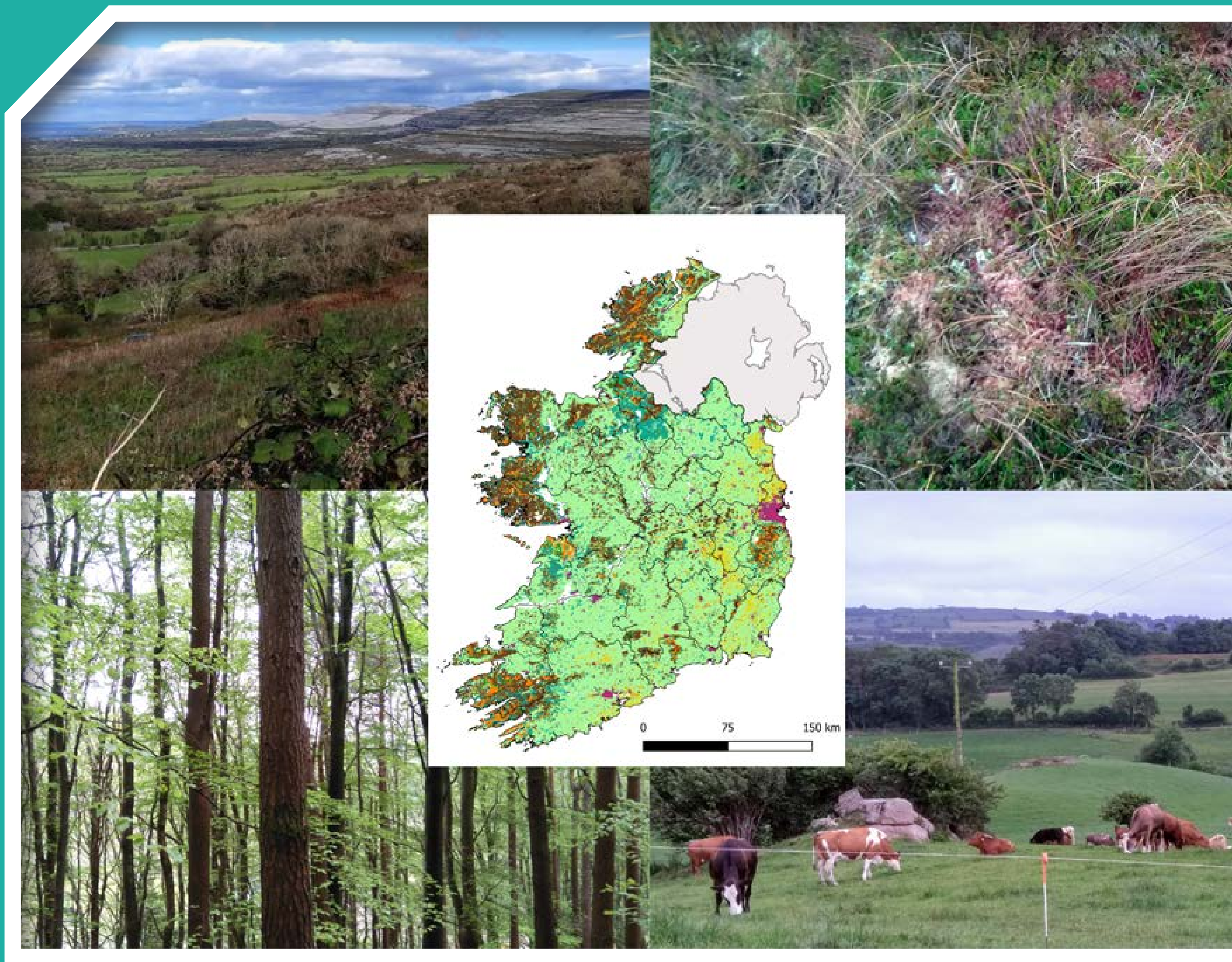
epa Research

Report No.371

Climate Change and Land Use in Ireland

Author: Eamon Haughey



www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (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:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2021–2030

Climate Change and Land Use in Ireland

(2018-CCRP-FS.36)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Botany Department, School of Natural Science, Trinity College Dublin

Author:

Eamon Haughey

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

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research. This research was co-funded by the Department of Agriculture, Food and Marine.

The author would like to acknowledge the members of the project steering committee, namely Jennifer McElwain (Trinity College Dublin), Frank McGovern (EPA), Phillip O'Brien (EPA), Lisa Sheils (EPA), John McEntagart (EPA), Marc Kierans (formerly of EPA), John Muldowney (formerly of the Department of Agriculture, Food and the Marine – DAFM), Philip Blackwell (DAFM), Kevin Keegan (DAFM), Dale Crammond (DAFM) and Liam Brennan (DAFM).

This report is based on research carried out/data from March 2018 to October 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2021–2030

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-988-8 May 2021

Price: Free Online version

Project Partner

Dr Eamon Haughey
Botany Department
School of Natural Science
Trinity College Dublin
Dublin 2
Ireland

Current address
Department of Natural Sciences
Galway-Mayo Institute of Technology
Dublin Road
Galway
Ireland
Email: eamon.haughey@gmit.ie

Contents

List of Figures

List of Tables

Executive Summary

This report translates key findings from the International Panel on Climate Change (IPCC) Special Report on Climate Change and Land (SRCCL) into the context of the Irish land system. The SRCCL is particularly relevant for Ireland because of the specific challenges to climate change mitigation and adaptation presented by the country's land system and land use. This report informs policy in relation to the scale of these challenges. It identifies pressures in terms of greenhouse gas (GHG) fluxes from the land system and how these emissions relate to land use and its economic outputs. Finally, the report focuses on solutions in the form of an assessment of actions that can be taken to simultaneously address climate mitigation and adaptation in the land system. Knowledge gaps are identified and recommendations for future research are made.

Although land use in Ireland is dominated by grassland (61.0% in 2016) and related grassland-based agriculture, there is significant variation in the intensity of grassland management across farming systems. Economically, agricultural outputs are dominated by ruminant livestock in the form of dairy and beef production. However, pigs, cereals (barley, wheat and oats), sheep, poultry, potatoes and mushrooms are also important. The area of forestry in Ireland has increased dramatically over the last century, from around 1.4% in 1918 to around 10.7% in 2016. However, the forest area remains relatively low compared with the average for the first 28 Member States of the EU (EU-28), and the rate of afforestation has slowed in recent decades. Peatlands cover a significant area but are largely degraded by human activities such as peat extraction. A national land use map, including data on land use intensity, would enable a better understanding of the dynamics of the land system in Ireland and facilitate targeted implementation of actions.

Current data on the principal land-based GHGs – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – were summarised and assessed. Over the period 2010–2017, agriculture contributed 28.8% of GHG emissions in Ireland, a substantially larger portion than the EU-28 average over the same period (10.3%). This contrast was driven by the dominance of ruminant livestock production and a relatively low level of heavy industry in Ireland. Again in contrast to the EU-28, the land use, land use change and forestry (LULUCF) category was a net source of GHGs in Ireland between 2010 and 2017. Agricultural emissions are dominated by CH_4 emissions from ruminant livestock and manure management and by N_2O emissions resulting from fertiliser use and soil management. Despite improvements in production efficiency in the agriculture sector, expansion and intensification have led to increases in absolute GHG emissions over the last decade. Forestry is an important net carbon sink, but its contribution is likely to decline in the coming decades as the rate of afforestation is decreasing. Peatlands and organic soils under agricultural management are significant GHG sources, but there is large uncertainty regarding actual GHG emissions from these lands, and their extent and drainage status represents a key knowledge gap.

The potential of 40 integrated response options to contribute to climate mitigation and adaptation and other land system challenges was assessed for Ireland, with 12 of the options found to be highly applicable. Options considered highly applicable in terms of potential to mitigate climate change, particularly at an individual consumer level, include dietary change, such as a shift towards "sustainable healthy" diets, and a reduction in food waste. Actions aimed at increased food productivity and improved grazing land and livestock management also have high potential but could lead to "rebound effects" in terms of absolute environmental footprint. Agroforestry and agricultural diversification are highly applicable, yet these options face considerable barriers to uptake by landowners, and a review of current policies is recommended. Although afforestation and bioenergy have considerable mitigation potential, they could have negative impacts on biodiversity and increase land competition if implemented at large scales. The restoration of peatlands and organic agricultural soils represents a major opportunity to reduce GHG emissions and create carbon sinks, but positive outcomes require major investment and may be limited by site-specific constraints. Biodiversity conservation goals may be more likely to succeed where integrated with land use planning including climate mitigation and adaptation strategies. Implementation of land-based response options requires a sustainable land management approach, one in which local communities and landowners are actively engaged in the planning and implementation process.

1 Background and Context

The intent of this report is to translate key findings from the Intergovernmental Panel on Climate Change's (IPCC's) Special Report on Climate Change and Land (SRCCL) into an Ireland-specific context. The report examines in detail the current status of land use in Ireland as well as the associated greenhouse gas (GHG) fluxes. Options available to address climate change mitigation and adaptation in the land system are analysed.

1.1 IPCC Special Report on Climate Change and Land

The IPCC's SRCCL was approved by governments in Geneva, Switzerland, in August 2019. This report was the second of three special reports of the sixth IPCC assessment cycle (AR6), building on the Special Report on Global Warming of 1.5°C approved in 2018, and preceding the Special Report on the Ocean and Cryosphere in a Changing Climate in September 2019. The SRCCL was prepared under the scientific leadership of IPCC Working Groups I, II and III in cooperation with the Task Force on National Greenhouse Gas Inventories. It was produced following requests from seven member governments, including the Irish government, and observer organisations for a report focusing specifically on land and its interactions with climate change. The SRCCL identifies the risks to human and natural systems presented by climate change, and assesses what can be done to address these risks. The SRCCL is of particular interest in an Irish context owing to the importance of the land system to the national economy and the relatively large proportion of GHG emissions that come from land.

The SRCCL summary for policymakers condenses hundreds of pages of assessment into a 34-page document. This summary synthesised key findings from the report using four sections: (A) People, land and climate in a warming world; (B) Adaptation and mitigation response options; (C) Enabling response options; and (D) Action in the near-term.

1.2 High-level Summary Messages

- Land is a critical resource upon which we all rely, but it is under increasing pressure from humans and climate change.
- Climate change is making a challenging situation worse, undermining food security and exacerbating desertification and land degradation.
- Through sustainable management, land can be an important part of the solution to climate change, but land cannot do it all.
- Coordinated and early action is required to tackle climate change; this can simultaneously improve land, food security and nutrition.
- Acting early to tackle climate change is more cost-effective, as it avoids losses, and more land-based response options are available to tackle climate change at lower levels of warming.
- There are many available response options that can be deployed now at relatively low cost.
- Many response options can deliver carbon sequestration in soils and biomass. However, carbon sinks are vulnerable to climate change and depend on sustainable management.
- Reducing GHG emissions from all sectors is essential if global warming is to be kept to well below 2°C.
- Delaying deep mitigation in other sectors shifts the burden to the land sector, increasing risks to food security and ecosystem services.

1.3 What the Land Report Ireland Sets Out to Do

This report translates key findings from the SRCCL into the context of the Irish land system. The general approach taken in this report is a sector-based one, with a regional breakdown of information where feasible. Chapter 2 focuses on a summary of the land system in terms of current status in land use, land use intensity and outputs. Specifically, land uses of interest include grassland, cropland, forestry and wetland/peatland areas. Consideration is also given to the economic importance of the various services provided by the land system. Chapter 3 assesses the GHG balance associated with different land uses using a sector-specific breakdown where possible. This is a key component of the report, since the interactions between land use and GHG fluxes have important implications for the mitigation commitments that Ireland has agreed to. Ireland needs to meet these commitments as part of its contribution to international efforts to mitigate climate change as set out in the Paris Agreement (2015).

An analysis of integrated response options to address climate change mitigation and adaptation goals, based on the SRCCL, is described in Chapter 4. Options for agriculture and forestry are explored and consideration is also given to value chain management for food, energy and other materials. A high-level summary of report findings, including the most relevant response options, as well as identified uncertainties and knowledge gaps, is provided in Chapter 5.

2 Land Use, Cover and Outputs

Land use, land use change through time and natural land cover are all linked to the climate system through the carbon, hydrological and nutrient cycles which underpin the functioning of terrestrial ecosystems (Chapin III *et al*., 2011). Through biophysical feedbacks, land use and cover affect climate conditions locally, regionally and globally. In turn, the way in which land is used is influenced by climate and, increasingly, by anthropogenic climate change (IPCC, 2019a). This chapter provides a high-level overview of land use, land use intensity and outputs from the land system in Ireland.

2.1 Land Use in Ireland and the EU

Currently, no national land use map for Ireland is available, somewhat hampering the monitoring of trends in land use change at a regional level. However, nationally, an analysis of land use data over the period 1990–2016 shows a relatively stable picture (Figure 2.1). The grassland area reduced slightly between 1990 and 2016, but grassland remains by far the most dominant land use in Ireland. The largest land use change over this period was in forestry, which increased from 7.0% in 1990–1994 to 10.7% in 2016. Comparing land use in 1990–1994 with 2016 levels, there was an 11.4% decline in the area of wetland recorded and an increase of 19.2% in the settlement area (Figure 2.1).

According to data from Eurostat (2015), land use in Ireland is markedly different from the average across the first 28 Member States of the EU (EU-28). The main differences are in the proportions of land devoted to agriculture, which in Ireland is 18.8% higher than the average in the EU-28, and to forestry, which in Ireland is 23.3% lower than in the EU-28. The area of land used for agriculture in Ireland is the second highest in the EU-28, with only Denmark having a larger agriculture area, at 63.1%. The relatively low level of forestry in Ireland is comparable to that found in the UK (7.1%) and Denmark (11.9%). Scandinavian countries tend to have the highest forestry areas, with Finland having the largest area, at 63.2% in 2015.

2.2 Grasslands in Ireland

Grasslands, accounting for 61% of land use in 2016, dominate land use and cover in Ireland (Figure 2.1). However, this category includes a spectrum of land use intensity across different soil and climatic

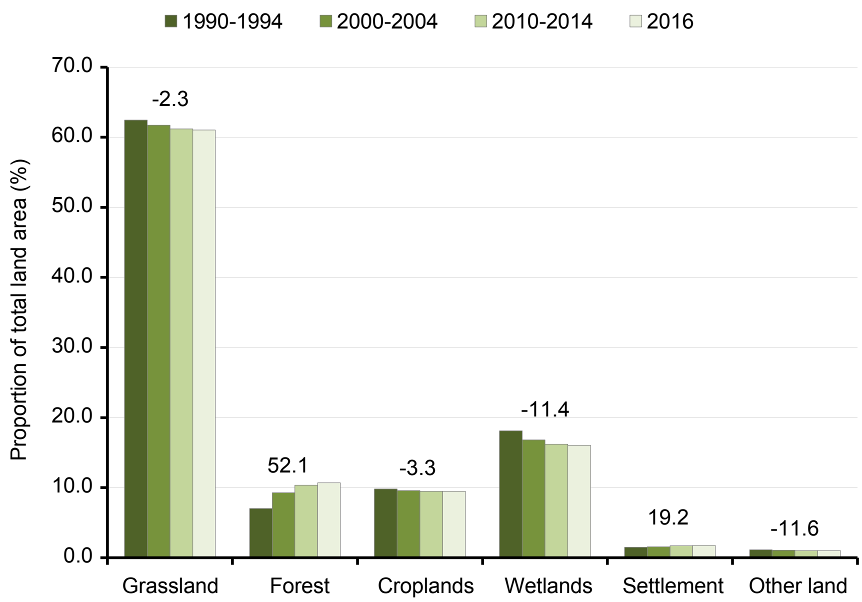


Figure 2.1. Land use in Ireland between 1990 and 2016, across six land use categories. Values shown above bars are the relative change in area from the period 1990–1994 to 2016. Data source: CSO (2018).

envelopes, from intensively managed pastures to seminatural habitat. Grassland-based agricultural systems support dairy, beef and sheep production, which together account for the largest proportion of the Irish agri-food sector. Permanent grassland makes up around 76% of utilised agricultural land in Ireland, significantly higher that the EU average of 33% (O'Mara, 2008). The climatic conditions in Ireland permit a relatively long grazing period, which enables a high level of grazed grass intake and therefore reduces the need for supplementary feed, which is economically favourable (Dillon, 2018). Beef cattle, dairy and sheep production are the dominant uses for grassland in Ireland. In terms of regional distribution, beef production is spread relatively evenly across the country, like the spread of grassland cover itself. While dairy production is more dominant in the southern half of the country, sheep production is concentrated in the upland parts of the north, west and south-east (O'Mara, 2008).

2.2.1 *Grassland-based outputs and land use intensity*

Grazing systems provide the basis for the production of ruminant livestock food products in Ireland, primarily beef, dairy products and sheep meat (O'Mara, 2008). Under the FoodWise 2025 plan the Irish government has set ambitious targets for growth in the agriculture sector, including an 85% increase in exports, to €19 billion annually by 2025, and a 65% increase in primary agricultural production (DAFM, 2015a). Since grassland-based agriculture dominates the landscape and the economic output from the agriculture sector (Table 2.1), it is expected that much of this growth will come from ruminant livestock products. To help meet these targets, as part of the FoodWise 2025 programme, a sectoral road map is produced every 3 years that identifies both industry production targets as well as "research targets", which provide a guide to the longer term production potential. An important part of this strategy is maximising the proportion of grazed grass in the total feed of animals, since utilised grass is the most cost-efficient feed (O'Donovan *et al*., 2018). However, there are widespread concerns that the planned expansion of agricultural outputs under FoodWise 2025 could have negative consequences for water quality and lead to biodiversity loss and an increase in absolute GHG emissions in the sector (EPA, 2016).

Table 2.1. Estimated agricultural production, economic value and indicators of land use intensity for Ireland

Sector	Production indicator	Output quantity (2018)	Value (2018, € million)	Farm size (ha)[a]	Stocking density (LU ha^{-1})[a]	N fertiliser (kg ha^{-1} year^{-1})[b]	P fertiliser (kg ha^{-1} year^{-1})[b]
Cattle – dairy	Volume of milk	7602 million litres	2555	58	2.06	129	9
Cattle – beef	Head of livestock	2,051,000	2261	31	1.14	39	4
Pigs	Head of livestock	3,860,000	459	–	–	–	–
Cereals[c]	Weight	1.4 million tonnes	288	60	–	158	25
Sheep	Head of livestock	2,487,000	253	48	1.10	30	5
Poultry	Head of livestock	92.1 million	168	–	–	–	–
Poultry	Eggs	1066 million	–	–	–	–	–
Potatoes	Weight	284,000 tonnes	139	–	–	–	–
Mushrooms	Weight	65,000 tonnes	117	–	–	–	–

Production indicators and estimated 2018 output quantity for each sector is based on CSO (2019a). The 2018 estimated value for each indicator output is based on CSO (2019b). Data on farm size and stocking density are 2018 sectoral averages; fertiliser inputs rates are 2015 sectoral averages. Sectors are ordered according to the estimated value.

[a]Farm size and stocking density are the 2018 averages based on the Teagasc National Farm Survey 2018 (Dillon *et al*., 2019). Farm size gives no indication of the area dedicated to the sector in question. Stocking density is expressed in livestock units per hectare (LU ha^{-1}), where a dairy cow is taken as the basic grazing livestock unit (i.e. value of 1) and all other livestock are given equivalents.

[b]Average inorganic nitrogen input and inorganic phosphorus inputs for 2015 (Wall and Dillon, 2017).

[c]Comprising barley, wheat and oats.

LU, livestock units.

Beef production

In 2018, the value of the beef industry to the economy in Ireland was €2.4 billion, and in excess of 530,000 tonnes of beef was exported, making Ireland the fifth largest exporter of beef in the world (DAFM, 2019). In the period 1980–2019, the highest annual total number of cattle in the country was 7.64 million, in 1998, while the lowest was 6.46 million, in 1988 (CSO, 2019c). A decline from the 1998 peak continued until 2011, at which point the national herd was at 6.49 million head. This sharp decline, especially from 1998 to 2000, was driven in part by changes to support provided to farmers from the Common Agricultural Policy (CAP) of the EU, which essentially decoupled payments from livestock numbers. This reduction in livestock numbers due to decoupling of payments to farmers led to reduced stocking rates across European regions, and in particular to those considered to be marginal agricultural systems, such as upland farms (Acs *et al*., 2010). From 2011 to 2017, the national cattle herd in Ireland increased by around 13%, to 7.36 million, with the rate of increase appearing to level off after 2017 (CSO, 2019c).

In 2018, the national average beef farm size was 31 ha, with a stocking density of 1.14 livestock units ha^{-1}, and in 2015 beef farms' average fertiliser application rates were 39 kg N ha^{-1} and 4 kg P ha^{-1} (Table 2.1). That rate of inorganic nitrogen fertiliser input is substantially lower than for dairy farms and slightly higher than for sheep farms. However, it has been recognised that, to meet FoodWise beef production targets for 2025, the average stocking density and level of fertiliser inputs on farms would need to increase (O'Donovan *et al*., 2018). Such an increase in herd size and intensity of management would clearly pose additional challenges in relation to the environmental sustainability of beef production systems. This would be of specific concern in relation to GHG emissions from the agriculture sector, as both the size of the national herd and use of nitrogen fertiliser are key determinants (section 3.2).

Dairy production

In 2018, milk production reached 7602 million litres, 4.4% more than in the previous year (Table 2.1) (CSO, 2019a). The value of the dairy sector to the economy was €4.6 billion in 2018, of which butter exports made up around €1 billion (DAFM, 2019). Much of the recent growth in the national cattle herd has come from the rapid growth of the dairy sector since 2011. Nationally, the number of dairy cows decreased from a peak of around 1.60 million in 1984 to a low of 1.06 million in 2005 (CSO, 2019c). However, between 2011 and 2018 the number of dairy cows increased by around 40.5%, reaching 1.50 million in 2018.

One of the primary drivers of growth in the national dairy herd was the elimination of EU milk quotas in 2015, which is also likely to have had an effect in the years preceding removal of the quota (Donnellan *et al*., 2015). Across the EU many dairy farmers have increased their herd size since 2015, and milk production increased by 4.5% in the 12 months following quota removal. However, the increase in Ireland over the same period was much more dramatic, at 18.4% (CSO, 2016). The higher increase in milk production in Ireland was probably due in part to the favourable production conditions, namely mild short winters and long grass-growing seasons and high grass utilisation (Donnellan *et al*., 2015). Despite a steady decline in the number of dairy cows from 1990 to 2005 (CSO, 2019c), the production of milk stabilised, indicating an increase in production per livestock unit (CSO, 2019a). From a low of 4804 million litres in 2009, milk production increased by 58%, to 7602 million litres, by 2018. This increase in production exceeds the growth of the national dairy herd, indicating that the efficiency of milk production continued to increase. In terms of intensity of land use, when compared with other livestock farming systems, dairy farms have the highest stocking rates and highest fertiliser inputs per hectare (Table 2.1). In 2018, the average size of dairy farms in Ireland was 58 ha (utilised agricultural area), with a stocking density of 2.06 livestock units ha^{-1}, which represents an increase of 0.16 livestock units ha^{-1} since 2010 (Dillon *et al*., 2019).

Sheep production

The size of the national sheep flock changed dramatically over the period 1980–2019 (CSO, 2019c). In 1980, the flock size was at its lowest over this period, at 3.2 million head; however, following a 12-year period of rapid growth, the number of sheep reached a peak of 8.90 million in 1992. The number stabilised above 8 million until 1998, following which there was a steady decline, reaching 4.75 million in

2010. In the 19 years since then the number of sheep has stabilised at between 5.0 and 5.15 million. The declining trend from 1998 is similar to that observed in total cattle numbers and was driven by decoupling of the CAP from livestock numbers as well as low prices over the period.

In general, it is possible to divide sheep production in Ireland into two types, hill based and lowland based, both of which primarily produce sheep for meat. The lowland sheep production system is predominantly grass based and accounts for around 85% of the total output (O'Mara, 2008). Hill farm-based sheep production dominates in the west and north-west of Ireland, and in this system, traditionally, most lambs are sold for finishing or breeding purposes in the lowland sector (O'Mara, 2008). In 2018, Ireland exported over 60,000 tonnes of sheep meat, worth around €315 million (DAFM, 2019). In June 2019, the national flock amounted to 5.14 million sheep, of which 2.48 million were breeding sheep (CSO, 2019a).

In terms of intensity of land use, when compared with other livestock farming systems, stocking rates and fertiliser application rates among sheep farms are similar to those of beef farms but are substantially lower than in dairy systems (Table 2.1). Similar to beef production, to meet government FoodWise 2025 targets for increased sheep production, stocking densities and fertiliser inputs on farms would need to increase (O'Donovan *et al*., 2018). In the case of the sheep sector, specific focus has been placed on the need to improve the efficiency with which farmers use feed inputs. Over-reliance on concentrated feed in particular has been identified as a key limitation of the economic viability of sheep farms and would need to decline substantially if growth in the sector is to be attained sustainably (O'Donovan *et al*., 2018). However, any increase in the size of the national flock or intensification of management would pose significant challenges to sustainability in terms of GHG emissions, soil health and water quality. Some areas may already have reached the limits of sustainable intensification, in that further intensification would lead to negative environmental impacts (Haughey *et al*., 2019). The differences between lowland and upland sheep farming in relation to vulnerability to land degradation should also be considered.

2.3 Cropland and Other Agriculture

2.3.1 *Cropland-based outputs and land use intensity*

In 2016, cropland accounted for approximately 9.5% of land use, 3.3% lower than in the period 1990–1994 (Figure 2.1). However, changes in cropland use are more dynamic than suggested by the overall change in cropland area. Large areas may enter and leave the cropland land use category on an annual basis (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 leaving cropland use, around 70% is returned to cropland within 5 years (Zimmermann *et al*., 2016). This demonstrates the importance of including in the cropland category those areas under temporary grassland to appropriately estimate the carbon losses and uptake associated with management of these areas.

In 2018, production of the three main cereal crops in Ireland, barley, wheat and oats, was 1.4 million tonnes, worth approximately €288 million, providing an important contribution to national food production and overall agriculture exports (DAFM, 2019). Since 1990 the primary types of cereal production have been barley followed by wheat (CSO 2019b). Although oats remain a small proportion of total cereal outputs the production has increased steadily over the past 20 years, with production more than doubling by 2017 compared with 1990 levels.

In terms of fertiliser inputs per hectare, on average, 158 kg N ha^{-1} and 25 kg P ha^{-1} were applied for cereal production in 2015 (Table 2.1). There was some variation across soil types, with less inorganic nitrogen applied in sites with more limited production potential than in less limited sites (Wall and Dillon, 2017). There is evidence that the efficiency of nutrient management could be improved. For example, over the period 2005–2015, farmers were under-applying phosphorus based on recommendations for replacement of the nutrients used to grow spring barley (Wall and Dillon, 2017), indicating that the long-term fertility of these soils could be reduced if this trend continues.

2.3.2 *Trends in other agricultural outputs*

Aside from grass-based ruminant livestock, the production of food from monogastric livestock such as pigs and chickens plays an important role in the Irish agriculture sector. In 2018, Ireland produced approximately 3.86 million pigs (Table 2.1), and exported pig meat was worth €828 million to the economy (DAFM, 2019). This level of pig production represents an increase of 52.5% compared with 1990 levels (CSO, 2019a). Pig production in Ireland is generally associated with a small direct land use footprint, as most pigs are reared intensively indoors (DAFM, 2016). The intensive production of pigs is highly concentrated: in 2014 just 320 farms accounted for most of the pig meat production in Ireland (DAFM, 2016). However, although the direct land use footprint of such production is small, an increase in pig numbers requires an increase in pig feed. Therefore, as a result of an increase in livestock numbers, the requirement for feed and the associated land use to produce feed for the national swine herd has grown substantially in the last 20 years. In some contrast to the pig sector in Ireland, in the UK the greatest growth in pig production in recent years has been in the outdoor bred or "high-welfare" pig farming model. In 2014, 42% of breeding pigs in the UK were kept in outdoor farming systems (DAFM, 2016). This move away from high-intensity indoor production in the UK has been driven largely by a combination of consumer and retailer pressure. Small-scale and low-intensity pig production in Ireland represents a small but growing proportion of the total output from the sector, with approximately 1500 producers registered with swine herds of fewer than 100 animals (DAFM, 2016).

In 2018, the export of poultry products, primarily chicken meat and eggs, was worth €278 million to the Irish economy (DAFM, 2019). There has been a steady increase in poultry meat and egg outputs over the last 20 years. The number of poultry produced increased from 50.9 million head in 1990 to 92.1 million head in 2018 (CSO, 2019a). Egg production increased dramatically between 2014 and 2018, rising from 637 million to 1066 million eggs. Also important is the production of mushrooms, which has increased significantly in Ireland since 1990, from 37,000 tonnes to 65,000 tonnes by 2018 (CSO, 2019a). Mushroom production is conducted entirely under cover and has a low land requirement but requires significant compost inputs, which has sustainability implications, as most of the compost used is peat based.

2.4 Wetland and Peatland

As well as providing a large carbon store, peatlands also provide other important services such as water filtration and water storage, with implications for flood management, biodiversity and tourism. Wetlands, including peatlands, accounted for 16.1% of land use in Ireland in 2016 (Figure 2.1). Irish peatlands may be subdivided into three main categories: upland or blanket bogs, raised bogs and fens (Renou-Wilson, 2018). Blanket bogs typically occur along the west coast and on 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. Both blanket and raised bogs may be described as ombrotrophic peat soils, while fens which are fed by groundwater are minerotrophic and are much less common (Creamer and O'Sullivan, 2018).

2.4.1 Peatland use and ecosystem services

Peatland in Ireland has historically and continues to be used for three main purposes: agriculture, forestry and extraction. The principal agricultural use of peatlands is cattle or sheep production, with an estimated 300,000 ha of organic soils (for a definition see Creamer and O'Sullivan, 2018) used for livestock grazing in Ireland (Wilson *et al*., 2013). In terms of intensity of use, much of this area may have undergone historical drainage to improve both the trafficability and productivity of the soil. Historical and ongoing nutrient additions to these lands may have also occurred to increase grass production. These management practices on organic soils under agricultural use have important consequences for their GHG emissions (Renou-Wilson *et al*., 2016). A significant proportion of Ireland's forestry plantations are on peat soils. The Forest Service has estimated that, between 1990 and 2000, 43.5% of total afforestation was on peatlands (Black *et al*., 2009). However, since the turn of the century this has been reduced dramatically (Renou-Wilson, 2018), and much of the forestry that remains on peatlands is now considered to have low production potential in terms of timber and other forestry outputs (Tiernan, 2008).

The third category of use for peatlands in Ireland is extraction. Extracted peat is used for energy generation, domestic fuel (heating) and horticultural products such as compost (Renou-Wilson, 2018). Although extraction for domestic fuel was traditionally carried out by hand, it has become largely mechanised over the last 50 years. There is much uncertainty regarding the extent of peatlands currently being used for domestic extraction, but it is estimated to affect around 500,000 ha. It is estimated that a further 100,000 ha of peatland has been used for industrial extraction, which was historically used for energy generation (Wilson *et al*., 2013). The other main user of extracted peat in Ireland is the horticultural industry, which uses peat as the basis of compost. In 2018, 821,148 tonnes of peat was exported from Ireland for use as peat compost, with the majority of that going to the UK (51.5%) and the remainder mainly to the EU (33.8%) (CHG, 2019).

2.5 Forestry Outputs and Trends

According to the National Forest Inventory (NFI), the area of forest land in Ireland increased from 1.4% of the total land area in 1918 to around 11.0% in 2017 (DAFM, 2018). In the early part of that period most of the forestry planting was undertaken by the state. In recent decades there has been a substantial increase in the area of privately owned forest, from 81,958 ha in 1973 to 378,663 ha in 2017 (DAFM, 2018). In 2017, the most common forest tree species was Sitka spruce, occupying 51.1% of the total forest area. Norway spruce, Scots pine, larch species and other conifer species made up a further 20.0%, with broadleaved species accounting for the remaining 28.9% of the forest area (DAFM, 2018). Native woodland and broadleaf planting have increased in recent years, with broadleaf planting rising from 21% of total planting in 2017 to 27% in 2018.

Despite the increase in total forestry area in Ireland, the rate of afforestation has decreased in the past 20 years. Annual afforestation in Ireland over the period 1922–2018 peaked in the 1990s, at over 23,000 ha per year; since then it has declined steadily, reaching around 4000 ha in 2018 (DAFM, 2019). Deforestation is also an on-going concern for forestry in Ireland and accounting for the rate of deforestation has implications for national GHG inventory calculations. Devaney *et al*. (2017) identified over 3000 deforestation events in Ireland over the period 2000–2012, which constituted around 5457 ha. These deforestation events principally resulted in land use changes from forest to settlement and from forest to grassland. However, Devaney *et al*. (2017) also found that a significant proportion of deforestation was related to peatland restoration works.

In line with global trends of increasing forestry product outputs, the production of roundwood[1] increased in the EU and Ireland over the period 1999–2018, and in particular after 2009 (Eurostat, 2018b). Compared with production of roundwood in 1999, production in the EU-28 had increased by 34.1% by 2018. In terms of outputs from the forestry sector in Ireland, in 2018, roundwood production was at the highest level since records began, at 3.54 million m^3 (Eurostat, 2018b). Roundwood supply forms the basis for several production streams, and forest product exports from Ireland were valued at €355 million in 2015. The breakdown of use for the 2015 supply of roundwood was as follows: sawn timber 30%, panel board production 25%, energy generation 35% and niche products 10% (COFORD, 2017). Of the energy generated from roundwood, 64% was used by timber processors in wood product production processes, 19% as firewood and 16% as woodchip fuel and wood pellets.

1 Roundwood comprises all quantities of wood removed from the forest and other wooded land, or other tree-felling site, during a defined period. Adapted from Eurostat (2018a).

3 Greenhouse Gas Fluxes in Terrestrial Systems

By 2017, human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels and are projected to reach 1.5°C between 2030 and 2050, should temperatures continue to increase at the same rate (IPCC, 2018). The biophysical driver of this temperature increase is the ongoing accumulation of long- and short-lived GHGs in the atmosphere. The focus of the assessment of GHGs in this report is on those gases most closely associated with the land system: carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). The IPCC's SRCCL investigated in detail the role played by land use, land use change, the food system and natural land in global GHG fluxes. Although, on a global basis, CO_2 is by far the most significant contributor to anthropogenic emissions and warming, when it comes to the land system, N_2O and CH_4 play a significant role. Since the terrestrial biosphere is both a source and a sink of CO_2 at the same time, partitioning between natural and anthropogenic emissions and removals is difficult. The general approach adopted by the IPCC since 2010 is to separate land-related GHG fluxes into three categories: (i) those that are direct effects of anthropogenic activity, such as land use and land use change; (ii) those that are indirect effects of anthropogenic activity including climate change; and (iii) those attributable to natural climate variability and natural disturbances (IPCC, 2010).

Globally, averaged over the period 2007–2016, total net anthropogenic GHG emissions amounted to 52.0 ± 4.5 Gt CO_2 eq. year^{-1}, of which 23% was attributable to the combined agriculture, forestry and other land use (AFOLU) sectors[2] (IPCC, 2019a). Of the annual average net anthropogenic GHG emissions, FOLU accounted for 13% of CO_2 emissions while AFOLU accounted for 44% of net CH_4 emissions and 81% of net N_2O emissions. The majority of CO_2 emitted from the global AFOLU sector over the period 2007–2016 was due to deforestation, which was partly offset by afforestation and reforestation. The large contribution of the AFOLU sector to emissions of CH_4 was driven largely by the enteric fermentation and rice production, while fertiliser/soil and livestock manure were the principal drivers of N_2O emissions (Jia *et al.*, 2019).

Compared with the annual average over the period 1990–1999, total GHG emissions in the EU-28 decreased by 5.0% over 2000–2009 and by 18.1% over the period 2010–2017 (Eurostat, 2019). In contrast, in Ireland, driven by strong economic growth, annual average emissions increased by 14.7% for the period 2000–2009 in comparison with 1990–1999 (Eurostat 2019). However, over the period 2010–2017, total GHG emissions in Ireland fell to similar levels to the 1990–1999 period (–0.6%). In the EU-28, the energy sector accounts for the vast majority of GHG emissions, averaging 84.0% over the period 2010–2017. In Ireland over the same period, the energy sector, although also accounting for the largest proportion of GHG emissions, was much less dominant than in the EU-28, accounting for only 58.3% of emissions.

3.1 Primary Land-related Greenhouse Gases

3.1.1 Carbon dioxide

Carbon dioxide is the single most significant anthropogenic GHG in the atmosphere, contributing approximately 66% of the total radiative forcing attributable to long-lived GHGs (WMO, 2019). In November 2019, the World Meteorological Organization (WMO) reported that globally averaged concentrations of atmospheric CO_2 reached 407.8 ppm in 2018, up from 405.5 ppm in 2017 (WMO, 2019). This represents a 46.7% increase in atmospheric CO_2 levels compared with the pre-industrial period (before 1750), when the concentration was 278 ppm. According to palaeoclimate data, the concentration of atmospheric CO_2 is now higher than at any time in at least the last 2 million years (Martínez-Botí *et al.*, 2015).

2 In the SRCCL, CO_2 eq. reporting was based on IPCC AR5 100-year global warming potential (GWP) values without climate-carbon feedback: N_2O = 265; CH_4 = 28.

The two primary categories of anthropogenic CO_2 emissions are emissions from the combustion of fossil fuels and the balance in relation to sinks and sources from the AFOLU sectors. From the end of the pre-industrial period until 2018, CO_2 emissions from the combustion of fossil fuels accounted for around 86% of cumulative anthropogenic emissions (Friedlingstein *et al*., 2019). Fossil fuel emissions include emissions due to the combustion of coal, oil and gas for the energy, transport and industry sectors. The annual average contribution of the AFOLU sectors to total global CO_2 emissions over the 2007–2016 period was 13%, with the remaining 87% coming from non-AFOLU anthropogenic sources (IPCC, 2019a). In Ireland, CO_2 is the most significant contributor to national GHG emissions. In 2018, CO_2 from the energy and industries sectors accounted for 26.8% and the transport sector for 31.1% of total CO_2 emissions, excluding land use, land use change and forestry (LULUCF) (EPA, 2020a). In terms of GHG inventories, CO_2 emissions from the land system in Ireland predominantly come from LULUCF and, to a much lesser extent, agriculture.

3.1.2 Nitrous oxide

Nitrous oxide (N_2O) is a long-lived and potent trace GHG that has an atmospheric lifetime of approximately 121 years and a 100-year global warming potential (GWP) 265 times that of carbon dioxide[3] (Myhre *et al*., 2013). The atmospheric concentration of N_2O has increased significantly since the pre-industrial era, from 270 ppb in 1750 to 331.1 ppb in 2018 (WMO, 2019), an increase of 22.6%. Importantly, the IPCC's SRCCL found with very high confidence that N_2O is "continuing to accumulate in the atmosphere at an increasingly higher rate" (Jia *et al*., 2019). In 2019, N_2O was estimated to contribute around 6% of the total radiative forcing of long-lived anthropogenic GHGs in the atmosphere (WMO, 2019). N_2O is generated by both natural processes occurring in soils and oceans, and anthropogenic activities including chemical fertiliser use, biomass burning and fossil fuel combustion. In both terrestrial and aquatic ecosystems, the primary source of N_2O is the remineralisation of organic material through the nitrification and denitrification processes (Butterbach-Bahl *et al*., 2013). Microbial nitrification and denitrification taking place in managed soils, natural soils and the ocean contribute more than 80% of total global N_2O emissions (Fowler *et al*., 2015).

3.1.2 Methane

The IPCC's SRCCL found with "very high confidence" that there is an on-going accumulation of CH_4 in the atmosphere (Jia *et al*., 2019). In 2018, the atmospheric concentration of CH_4 was approximately 1869 ppb, around 142% higher than the pre-industrial level of 772 ppb (WMO, 2019). As has already been noted, CH_4 emissions from AFOLU accounted for 44% of total CH_4 emissions over the period 2007–2016 (IPCC, 2019a). The latest data from the Global Methane Budget for the period 2000–2017 (Saunois *et al*., 2019) indicate that CH_4 remains stable in the atmosphere for approximately 9.6 years. Although CH_4 is a relatively short-lived GHG compared with CO_2 and N_2O, its accumulation in the atmosphere indicates that emissions are outstripping the rate at which it is broken down or removed. The complexity of the atmospheric chemistry associated with CH_4, and in particular in relation to the weighting factor that should be used to compare CH_4 with CO_2 and also how long it persists in the atmosphere, has led to considerable and on-going debate in the scientific literature (Balcombe *et al*., 2018).

3.2 Greenhouse Gas Emissions from Agriculture

Over the period 2010–2017, agriculture accounted for 10.3% of GHG emissions in the EU-28 (Eurostat, 2019). The share of GHG emissions from agriculture in Ireland is much larger than the EU-28 average, accounting for an average of 28.8% of total emissions over the 2010–2017 period. The large share of GHG emissions attributable to agriculture in Ireland is due to a combination of a relatively low level of heavy industry, resulting in lower energy emissions, and also an agriculture sector that is dominated by ruminant livestock (section 2.2.1), which have a higher CH_4 and N_2O emission footprint than, for example, monogastric livestock or crop production.

3 This GWP value comes from the IPCC AR5 assessment and does not include climate–carbon feedback. Including climate–carbon feedback gives N_2O a 100-year GWP value of 298. The lifetime of N_2O is the perturbation lifetime.

Over the period 1990–2018, total agriculture emissions in Ireland peaked in 1998, then over the following decade declined to a level similar to that in 1990 (EPA, 2020a). However, between 2011 and 2018, emissions showed an increasing trend, with total agriculture emissions increasing by 16.2% over that period (EPA, 2020a). Most emissions from agriculture are attributable to livestock CH_4, which accounted for 65.0% of agriculture emissions in 2018 (Figure 3.1) and includes CH_4 from both enteric fermentation and manure management. The second largest share of emissions was from N_2O related to agricultural soil management, which accounted for 29.5% (Figure 3.1). Nitrous oxide from soil management is primarily caused by inputs of inorganic nitrogen fertiliser to grassland and cropland. The N_2O emissions from livestock (manure management) and CO_2 emissions due to the use of lime and urea were less significant, making up approximately 5.4% of total agriculture emissions in 2018.

3.2.1 *Carbon dioxide fluxes from agriculture in Ireland*

In terms of the GHG inventory, the agriculture sector in Ireland accounts for a only small amount of direct CO_2 emissions, attributable to liming and the application of urea to agricultural soils. In 2018, these sources combined accounted for 2.7% of emissions from the agriculture sector (Figure 3.1), or around 0.9% of total national CO_2 emissions (EPA, 2020a).

3.2.2 *Nitrous oxide emissions from agriculture in Ireland*

In 2018, N_2O accounted for 32.2% of total estimated agricultural emissions in Ireland, with 29.5% attributable to agricultural soil management and 2.7% attributable to livestock (Figure 3.1). Between 1990 and 2018, total N_2O emissions from agricultural soils peaked in 1998, at 21,679 tonnes, following which there was a decline to a low of 16,658 tonnes in 2011 (EPA, 2020a). However, since 2011 there has again been an increasing trend in N_2O emissions, with an 18.7% increase from 2011 to 2018. Total emissions closely track the trend in direct emissions, which make up the vast majority of the category, accounting for around 90% of N_2O in 2018 (EPA, 2020a).

Although indirect emissions of N_2O from agricultural soils account for a small proportion of total soil emissions, they are still a significant category, with

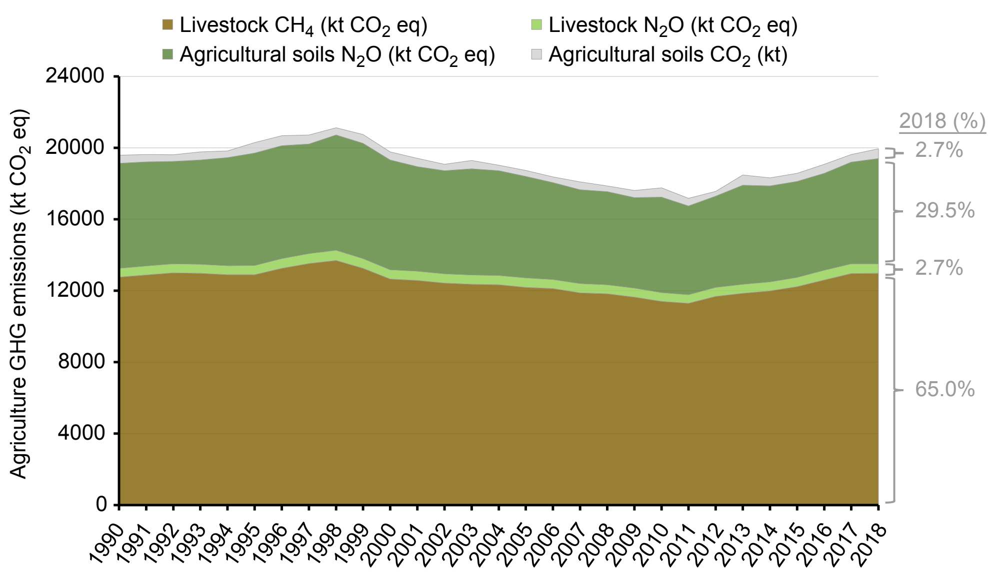


Figure 3.1. Estimated total annual emissions from agriculture in Ireland from 1990 to 2018 (stacked) with N_2O and CH_4 in CO_2 equivalents (calculated using 100-year GWP values, with weighting factors in line with IPCC AR4: $N_2O = 298$; $CH_4 = 25$). Agricultural soil CO_2 includes emissions from urea and limestone application, livestock CH_4 includes emissions from enteric fermentation and manure management, and livestock N_2O includes direct and indirect emissions from manure management. Data source: EPA (2020a).

estimated emissions of 1916 t N_2O in 2018 (EPA, 2020a). Indirect N_2O emissions from agricultural soils include emissions from two main routes, (i) atmospheric nitrogen deposition and (ii) nitrogen leaching and run-off (EPA, 2020a). Total emissions from livestock manure management represent a much smaller source of N_2O than emissions from agricultural soils. However, this category remains significant, with estimated total emissions of 1821.7 t N_2O in 2018 (EPA, 2020a). Although emissions from livestock manure are primarily in the form of CH_4, direct and indirect N_2O emissions also occur during the period in which livestock manure is stored and treated before application to soils. Direct emissions in this category occur as a result of nitrification and denitrification taking place in the manure, while indirect emissions are due to deposition of ammonia and other reactive nitrous oxides following volatilisation.

3.2.3 Methane emissions from agriculture in Ireland

In Ireland CH_4 emissions accounted for an estimated 65% of total GHG emissions from the agriculture sector in 2018 (Figure 3.1). These emissions are livestock based and are attributable to enteric fermentation in ruminant livestock and to manure management. Over the period 1990–2018, CH_4 emissions from enteric fermentation and manure management peaked in 1998, with an estimated 547.7 kt CH_4 emitted that year. Following this peak, CH_4 emissions declined to a low of 451.9 kt CH_4 in 2011, since when emissions have again increased dramatically, reaching 518.8 kt CH_4 in 2018 (EPA, 2020a). The trend in total CH_4 emissions has tracked very closely that of the dominant contributor: CH_4 emitted from enteric fermentation and manure management of cattle (EPA, 2020a). In 2018, CH_4 emissions from cattle made up 90.4% of total CH_4 emissions from the agriculture sector in Ireland, with sheep accounting for 6.0% and swine and other livestock the remaining 3.6%.

3.3 Greenhouse Gas Fluxes from Land Use, Land Use Change and Forestry

According to global models, between 2007 and 2016, land use and land use change accounted for estimated net CO_2 emissions of 5.2 ± 2.6 Gt CO_2 year^{-1} (IPCC, 2019a), primarily driven by deforestation but partly offset by afforestation/reforestation. Although there was no clear trend over that period, average CO_2 emissions have remained consistently significant at 4.8 ± 0.6 Gt CO_2 year^{-1} (IPCC, 2019a). Since 1990 LULUCF has been a net sink of GHG emissions across the EU-28. This sink, primarily due to forestry, accounted for an average removal of 295.3 Mt CO_2 eq. year^{-1} over the period 2010–2017. In contrast, the LULUCF sector in Ireland was a net source of GHG emissions, accounting for 4.6 Mt CO_2 eq. year^{-1}, or 7.3% of total emissions, over the period 2010–2017 (Eurostat, 2019).

Land use change can result in altered rates of N_2O emissions depending on the type of land use change and intensity of land use following change. The conversion of natural forest or herbaceous ecosystems, including natural grasslands and shrubland, to anthropogenic use typically results in an initial increase in N_2O emissions (which may last for over a decade) regardless of the type of anthropogenic use (McDaniel *et al.*, 2019). However, in the longer term there are strong interactions between land use intensity and emissions rates. In the absence of soil fertilisation, emissions tend to decrease over time (Jia *et al.*, 2019). However, fertilisation of converted land is generally not associated with a decline in N_2O emissions over time, and there is a relatively direct relationship between the rate of fertiliser inputs and emissions, moderated by soil and climatic conditions (Jia *et al.*, 2019).

3.3.1 Carbon dioxide fluxes from LULUCF in Ireland

In Ireland, LULUCF was a source of GHG emissions in all years from 1990 to 2018, and the vast majority of those emissions were in the form of CO_2. Fluxes of GHGs attributable to LULUCF can, as shown in Figure 3.2, be broken down into two main components: sources comprising emissions from grassland, wetland and forest soils; and sinks provided by the forestry biomass. Grassland and wetlands are the primary sources of CO_2 emissions due to LULUCF, with croplands a net sink in some years but a source in others. However, owing to the complex dynamics of land use change between categories, and the difficulty of partitioning emissions between soils and biomass,

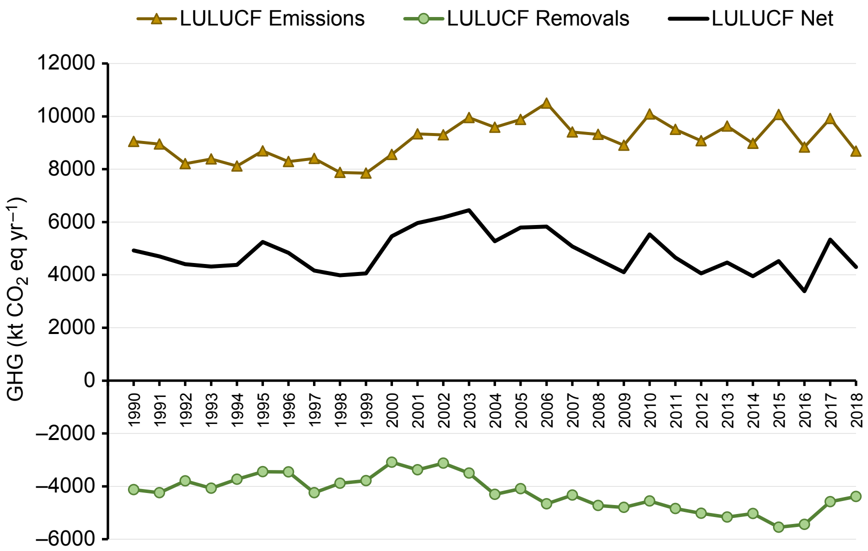


Figure 3.2. Estimated annual GHG emissions and removals attributable to LULUCF in Ireland from 1990 to 2018 (in CO_2 equivalents calculated using 100-year GWP values and with weighting factors in line with IPCC AR4). Removals include the sum of negative emissions attributable to forestry and harvested wood products. Emissions include the sum of emissions from grassland, cropland, wetland, settlements and other land. Data source: EPA (2020a).

there is a high degree of fluctuation in estimates across the period 1990–2018 (EPA, 2020a).

The forestry sector in Ireland acted as an important net sink of CO_2 between 1990 and 2018 (EPA, 2020a). According to the NFI, in 2017, the carbon reservoir of forest estate, including carbon in above- and below-ground biomass, litter and soils, amounted to an estimated 311.7 MtC (DAFM, 2018). Any examination of the forestry sector in terms of its carbon stock and on-going removal of carbon needs to consider three main components: (i) forest biomass, comprising above- and below-ground biomass and litter; (ii) forest soils; and (iii) harvested wood products. Although it decreased over the period 1990–1999, annual CO_2 removed by forest land use has increased since 2000 (EPA, 2020a). The vast majority of the 311.7 MtC stored in forestry is in the soil pool, making up 79.1% of total carbon. The two other main carbon stock pools in the system are above-ground and below-ground biomass, accounting for, respectively 14.1% and 3.3% of carbon in 2017. Reflecting the increase in forest area and growth of existing forest stands,[4] there has been an increase in the amount of carbon stored in above-ground biomass, from 30.6 Mt in 2006 to 45.6 Mt in 2017 (DAFM, 2018).

The other component of annual removals of carbon from forestry is harvested wood products. Carbon removals in harvested wood products increased from the early 1990s through to 2007 and has stabilised at a lower level since 2008 (EPA, 2020a). The amount of carbon stored in the harvested wood pool depends on the production streams followed by the harvested timber. IPCC guidelines on inventory calculation of carbon storage in harvested wood are based on product type and expected product life cycle (IPCC, 2006). Therefore, the proportion of harvested wood used for long-lived products, such as construction materials, relative to the proportion used to produce short-lived products, such as paper or biofuel, affects the net carbon balance of the forestry sector (Matthews *et al.*, 2015; Olsson *et al.*, 2019). In 2015, 55% of the roundwood supply in Ireland was used to make sawn timber and panel boards (COFORD, 2017), which have the potential to provide a much longer carbon store than timber used for energy generation.

4 A forest stand is defined as a contiguous area of forest that contains a relatively homogeneous set of trees, or trees sharing a common set of characteristics. Stands are often treated as units for the purposes of forest management and data collection.

Despite the removals provided by forest land and harvested wood products, which are a major carbon sink, in each year from 1990 to 2018 LULUCF was a net source of GHG emissions in Ireland (Figure 3.2). This is the result of emissions from grasslands and wetlands which are major sources of CO_2 due to the drainage of organic soils. While there is no clear trend in net GHG emissions from LULUCF, an increase in annual carbon removals since around the year 2000 has been cancelled out by an increase in emissions. The cropland, settlements and other land categories are also sources of LULUCF emissions but are comparatively less important than grassland and wetlands. Note that the dynamics of land-use change between categories and the relative contributions from biomass and soils are complex and this leads to large fluctuations in the estimates of annual emissions and removals (EPA, 2020a).

3.3.2 *Nitrous oxide emissions from LULUCF in Ireland*

In Ireland, N_2O emissions from LULUCF represent a small proportion of the total GHG flux associated with LULUCF, which is dominated by CO_2. However there has been a strong increasing trend in N_2O emissions from LULUCF since 1990 (EPA, 2020a). In 2018, combined N_2O emissions from forest land, grassland, wetlands, settlements and other land, and croplands was 1358 t N_2O (EPA, 2020a). This represents an increase of over 180% in N_2O emissions from this category compared with 1990 levels. This large increase in N_2O emissions was driven by change in several subcategories. Over the period 1990–2018 there was a steady increase in N_2O emissions from the forestry sector. The main component of N_2O emissions from forestry are emissions from soils related to drainage activity in forest land. The drainage of forest land that remains forested (i.e. was already in the forestry category of land use when drainage took place) accounted for emissions of 280 t N_2O in 2018, which is a small decrease on 1990 levels (EPA, 2020a). The increased emissions from forestry was driven by the drainage of land converted to forestry, from 10 t N_2O in 1990 to 320 t N_2O by 2018 (EPA, 2020a). Estimated N_2O emissions from the settlements and other land use categories were the second largest source in the LULUCF category, and increased rapidly from the late 1990s to a peak around 2009. This increase in emissions was associated with an increased rate of land use change to the settlement category during this period of economic growth.

3.3.3 *Methane emissions from LULUCF in Ireland*

In 2018, CH_4 emissions from LULUCF in Ireland were estimated at 18.4 kt CH_4 with the majority of those emissions attributable to grassland (55.7%), with wetlands and forest land contributing the vast majority of the remainder (EPA, 2020a). Since 1990, CH_4 emissions from LULUCF have varied considerably from year to year, owing to spikes in estimated emissions from wetlands. Over this period, there was no clear trend, either increasing or reducing, in CH_4 emissions, with average LULUCF emissions of 18.0 kt CH_4 $year^{-1}$ from 1990 to 2018 (EPA, 2020a).

Grassland CH_4 emissions are primarily associated with drainage activity occurring on organic soils that are under grassland management. The methodology used in the national GHG inventory to estimate CH_4 emissions due to drainage activity on organic grassland soils requires estimation of the area affected by drainage, as well as an estimate of the number or density of drainage ditches constructed (EPA, 2020a). However, there is high uncertainly regarding the actual number of drainage ditches and their current functional status, especially where drainage activity occurred decades ago. There is also likely to be large seasonal and interannual variation in the water levels within drainage ditches, and this affects the relative dominance of anaerobic conditions that lead to CH_4 emissions (Sirin *et al*., 2012). A small proportion of grassland CH_4 emissions, estimated at less than 0.40 kt CH_4 in 2018, is attributable to burning and wildfires (EPA, 2020b).

Wetlands make up the second largest source of CH_4 emissions in the LULUCF category (EPA, 2020a). Drainage activity data are a key input used in the calculation of CH_4 emissions from wetlands. The approach taken in the national GHG inventory is similar to that used for grasslands and requires estimation of the area of wetland impacted by drainage and estimated density of drainage ditches constructed. High interannual variability in wetland CH_4 emissions is driven in part by the effects of wildfire occurring on wetland areas, which had peaks in 2010 and 2017 (EPA, 2020a).

4 Integrated Response Options

The IPCC, in its SRCCL, assessed a range of options to address five “land challenges” of climate change mitigation and adaptation, tackling desertification and land degradation and enhancing food security (IPCC, 2019a). The extent and severity of the challenges currently facing the land system vary in different regions of the world. However, in the future these challenges are likely to increase due to climate change, and they may be further exacerbated or alleviated depending on socioeconomic development pathways (Smith *et al*., 2019). Integrated response options are defined as those options that simultaneously address more than one challenge facing the land–climate system. This integrated approach highlights the potential for co-benefits but also indicates where trade-offs are necessary (IPCC, 2019a).

4.1 Overview of Integrated Response Options

The IPCC’s SRCCL assessed the global potential of 40 integrated response options, which are summarised in Table 4.1. The descriptions provided are primarily based on Tables 6.5–6.12 of the SRCCL (Smith *et al*., 2019). This is supplemented with information from other sections of the SRCCL Chapter 6, as well as from Chapter 4, Land Degradation (Olsson *et al*., 2019); Chapter 5, Food Security (Mbow *et al*., 2019); and Chapter 7, Risk Management and Decision Making in Relation to Sustainable Development (Hurlbert *et al*., 2019).

Note that many of the response options encompass a suite of actions, and actions often form part of multiple response options. In the case of agricultural land management, for example, increasing food productivity may involve changes to cropland, grazing land and livestock management, which are separate sets of response options in their own right. Several of the options aimed at increasing food productivity may also result in an increase in soil carbon stocks, and so these options overlap with soil-based land management. Response options should not be summed or regarded as entirely mutually exclusive interventions.

4.1.1 *Applicability of response options to Ireland*

The efficacy of the response options is strongly affected by local environmental and socioeconomic conditions. Therefore, the value of a global assessment for estimating potential at the regional or local level is limited. Some response options may only be applicable to specific ecosystems, climate zones or economic sectors. In the case of others, the potential level of deployment in Ireland may be limited because the land system to which it applies covers only a small area. And in some cases, response options that currently have limited applicability to Ireland could become more applicable in the future as the result of climate change. To take these issues into account, the specific potential of integrated response options for Ireland was assessed. The purpose of this assessment was to identify the options that could have the largest positive impact on climate change mitigation and adaptation goals in Ireland. To this end options were categorised as having low potential (L), moderate potential (M) or high potential (H) based on the following criteria:

- **Low potential applicability:** a response option that is currently not applicable or applicable only to a relatively small[5] area of natural or managed land in Ireland. In the case of response options applicable to a sector of the land system (including the food system), a response option of low potential applicability is one that is currently not applicable to any sector, or is only partly applicable to one or more sectors in Ireland.
  - – Or a response option that meets the main criteria for moderate potential applicability but is “effectively” in place already or near the point of saturation.

5 A small area is defined as <1 %, a moderate as > 1% but < 5% and a large area is defined as > 5% of total land cover area based on CORINE 2018 data.

- **Moderate potential applicability:** a response option that is currently applicable to a moderate[6] area of natural or managed land in Ireland. In the case of response options applicable to a sector of the land system (including the food system), a response option of moderate potential applicability is one that is currently applicable to at least one major[6] sector or multiple minor[7] sectors in Ireland.
  - Or a response option that meets the main criteria for high potential but is "effectively" in place already or near the point of saturation.
  - Or a response option that currently has low potential but whose potential is likely to increase in the future as a result of climate change.
- **High potential applicability:** a response option that is currently applicable to a relatively large[5] area of natural or managed land in Ireland. In the case of response options applicable to a sector of the land system (including the food system), a response option of high potential applicability is one that is currently applicable to multiple major[6] sectors in Ireland.

A description of each option, along with the outcome of the assessment of its potential applicability to Ireland, is provided in Table 4.1. Further information on the assessments and associated caveats is provided in Table A1.1. Detailed analysis of each of the options assessed as having high potential applicability to Ireland is provided in sections 4.2 and 4.3.

4.2 Response Options Based on Value Chain and Risk Management

A value chain may be broadly defined as a set of activities by which an organisation or producer delivers a product or service to the marketplace. Typically, value chains related to the land sector have become more developed and complex in conjunction with overall economic development. In the agriculture sector, development of value chains has historically been related to increased farm incomes but has not necessarily delivered benefits to all consumers (Bodnár, 2011). Indeed, there are complex interactions between the global development of value chains and food security. The combination of delivery of a value chain and improvements in food production is likely to have the greatest chance of positive outcomes for all societal groups (Hurlbert *et al.*, 2019). Two subcategories of value chain management options were assessed in the SRCCL: demand management and supply management. Demand management refers to the parts of the value chain that are directly connected to the consumers of products and services, who may be individual consumers or organisations. Of the demand management options assessed, two were found to be highly applicable to Ireland: dietary change and reduced food waste. Supply-side management refers to the parts of value chains that link raw material production, processing and transport for retail. None of the five supply chain management options assessed was found to be highly applicable to Ireland.

Risk is a central concept in understanding the potential for adverse effects of climate change on human or ecosystems. In the SRCCL, risk is generally defined as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems" (IPCC, 2019b). In the context of response options, risk management refers to plans, strategies or policies aimed at reducing the likelihood and/or magnitude of adverse consequences associated with assessed risks. Five response options were assessed under the risk management category; however, none was found to be highly applicable to Ireland.

4.2.1 Dietary change

Some dietary choices require more land and water and have more GHG emissions associated with them than others (IPCC, 2019a). Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, present large opportunities for adaptation, limiting the effects of climate change and have health co-benefits (Mbow

---

6 The major agricultural production sectors are (based on Table 2.1) cattle – beef, cattle – dairy, pigs, cereals (barley, wheat and oats), sheep, poultry, potatoes and mushrooms. Other major sectors include value chains related to the main agricultural production sectors and commercial forestry and associated harvested wood products.

7 Minor sectors are those not included in the listed major sectors but which currently exist in Ireland, for example horticultural production in the agriculture sector.

Table 4.1. Descriptions and examples of application of the 40 integrated response options assessed in SRCCL, categorised by response option category

Response category	Response option	Description/examples	Rating
Value chain management			
Demand management	Dietary change	Dietary change can reduce pressure on land systems (by reducing demand for land) and lower GHG emissions, with co-benefits for human health A shift in towards "sustainable healthy" diets is especially relevant in regions and countries where there is overconsumption in terms of overall calorie intake and/or where animal-sourced protein is high. Where groups/ populations do not meet minimum nutritional needs, change would involve increased consumption of some foods Examples include shifts towards diets featuring more plant-based foods such as coarse grains, legumes, fruits and vegetables, nuts and seeds However, the transition to low-GHG-emission diets will be influenced by local production practices, technical and financial barriers, and by cultural habits	H
	Reduced post-harvest losses	Reducing food loss at the harvest, storage and transport stages of the food system can improve food security This may involve improvements in technology and supply chain management. Post-harvest losses are the most dominant form of food loss and waste in the developing world	L
	Reduced food waste (consumer or retailer)	Reducing food waste at the consumer or retailer stages of the food system can reduce pressure on the land system This form of food loss and waste is dominant in developed countries and regions	H
	Material substitution	Substitution of GHG-intensive building materials (such as concrete, iron, aluminium) with timber or agricultural biomass can have benefits for climate change mitigation The lifespan of the substituted material largely determines carbon storage duration	M
Supply management	Sustainable sourcing	Encompasses a wide range of approaches including standards and certification to ensure that the production of goods is sustainable Examples include forest certification programmes or food producers who are supported by fair trade initiatives. Certification of forestry accounts for 25% of global roundwood production	M
	Management of supply chains	This involves a set of approaches to improve the efficiency and sustainability of supply chains Examples include reducing the GHG footprint of supply chains (energy efficiency and shortening) and efforts to improve market stability, for example by enhancing food storage capacity	L
	Enhanced urban food systems	Improving access to nutritious food in urban areas can have co-benefits for food security and human health Examples include urban or periurban agriculture, market gardens and farmers' markets. May include the use of novel technologies such as vertical farming and the use of controlled environments	L

Table 4.1. Continued

Response category	Response option	Description/examples	Rating
	Improved food processing and retailing	More efficient food processing and retailing can reduce the overall GHG footprint of the food system and enhance food security Examples include use of (and innovation to achieve) more efficient technologies in processing operations. Can be strengthened by public–private initiatives including research and development	L
	Improved energy use in food systems	Energy efficiency can be improved throughout the food system by reducing reliance on GHG-intensive energy sources and moving towards renewables Gains can also be made by reducing overall inputs (or increasing outputs per unit input), but rebound effects may occur (see Figure 4.1)	M
Risk management			
	Management of urban sprawl	Urban sprawl is a global threat to the loss of agricultural, forest and natural land. Prevention of urban sprawl may provide adaptation co-benefits Management approaches include integrated land use planning and agricultural land designation (or zoning)	M
	Livelihood diversification	Household dependence on a small number of income sources can make them economically vulnerable to climate change, especially in the agriculture sector Diversification can provide other income streams that could include, for example, mixed farming, high-value farming (such as organic), agroforestry, added-value products (e.g. artisanal food products), accessing markets directly (e.g. farmers' markets), tourism or off-farm employment	M
	Use of local seeds	Can reduce dependency on commercial seeds and reduce associated costs and market exposure. However, local (unimproved) seeds may have lower productivity Use of local seeds is particularly important in the developing world	L
	Disaster risk management	A range of measures can be used to minimise negative outcomes resulting from climate-related disasters and events on socioeconomic systems Examples include hazard and risk mapping, hydrological and meteorological monitoring and early-warning systems and related education and outreach	M
	Risk-sharing instruments	Such instruments can help buffer the negative effects of extreme climate events on society In agriculture a prime example of this is commercial crop insurance, which can help manage risks associated with crop failure (due to, for example, extreme climate events) or price fluctuations	M
Land management			
Agriculture land management	Increased food productivity	This is an efficiency-based approach: increased productivity is defined as an increase in the output of agricultural produce per unit area of land or water Increased productivity at the expense of negative externalities such as a decrease soil health or water quality or a negative impact on biodiversity is unsustainable. Note that this option overlaps with many other efficiency-focused response options in the agricultural land management category	H

Table 4.1. Continued

Response category	Response option	Description/examples	Rating
	Improved cropland management	A collection of approaches to cropland management that are region and crop specific can reduce GHG emissions, increase soil carbon and increase system resilience to climate change Improved crop management • alternative management for increased soil carbon such as minimal tillage • improved crop cultivars (through plant breeding) • optimised crop rotations, use of cover crops and perennial cropping system Improved nutrient management • optimised fertiliser application rates and timing • use of crop-specific fertilisers and/or fertiliser with nitrification inhibitors • optimised soil pH through liming • other examples focused on water management and the use of biochar/crop residues	M
	Improved grazing land management	A collection of practices focusing on the management of grasslands and aimed at reducing GHG emissions and increasing soil carbon and resilience to climate change Grazing land vegetation management: • improved grass cultivars (through plant breeding) • multispecies swards including legumes and deep-rooting species (for increased productivity, nutritional quality and resilience to extreme climate events) • optimal nutrient management (e.g. soil pH, quantity and timing of organic and synthetic fertiliser application) Management of grazing livestock: • optimal stocking density and grazing rotations – based on local soil–climate conditions (reducing land degradation)	H
	Improved livestock management	Approaches to livestock management that aim to reduce GHG emissions from enteric fermentation and manure management (which includes manure from non-ruminants) • improved animal feed quality or the inclusion of dietary additives to increase productivity and/or reduce CH_4 emissions • animal breeding • animal management • manure management	H
	Agroforestry	“Land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence” (IPCC, 2019b) Can (potentially) increase carbon sequestration in soils and biomass (on the same unit of land) with co-benefits for climate change resilience	H
	Agricultural diversification	Encompasses a range of approaches that aim to increase the resilience of farms (and farm households) to climate variability, climate change and associated economic risks The general approach is to shift the farming system away from a single, typically low-value, agricultural output to a more diverse set of outputs including those with higher or added value	H

Table 4.1. Continued

Response category	Response option	Description/examples	Rating
	Reduced grassland conversion to cropland	The conversion of grasslands to cropland results in soil carbon losses due to the process of cultivation (which results in oxidation of soil carbon) and soil erosion Conversion of grasslands often occur because of food security challenges and there may trade-offs between this option and food security	L
	Integrated water management	Management of water resources to reduce aquifer and surface water depletion, prevent overextraction and thereby increase resilience to extreme climate events such as drought Examples include the use of more efficient irrigation technologies such as micro-drip irrigation or increasing soil carbon content, which can enhance water retention	M
Soil-based land management	Increased soil organic carbon content	Encompasses a range of activities (overlapping with several other response options) that aim to increase soil organic matter content including: • land use change (e.g. from cropland to forest/grassland) • vegetation management (e.g. perennial crops) • nutrient management (e.g. increased organic inputs) • crop management (e.g. minimum tillage and crop residue incorporation) Some trade-offs with agricultural productivity may be necessary, and mitigation potential is both soil and system specific	M
	Reduced soil erosion	Management practices that reduce soil erosion include crop management that minimises soil disturbance (such as minimum tillage) or maintains continuous soil cover (such as cover crops) Particularly important for maintaining the long-term productivity potential of cropland soils	L
	Reduced soil salinisation	Salinisation of soil is a major land degradation process that undermines soil health and productivity, often occurring in dryland areas. Options to address this include improved water resource (irrigation) management and incorporation of organic matter in soils Sea level rise is increasingly having a negative impact on soils and groundwater quality. It is recognised that, although this can be addressed by physical infrastructure in many cases, adaptation may not be possible	L
	Reduced soil compaction	Soil compaction can have a significant negative impact on soil health and functioning Options to reduce it include the control of agricultural traffic (avoiding traffic during periods of soil water saturation), adapted farm machinery and appropriate management of livestock density	M
	Biochar addition to soil	Biochar is a product of pyrolysis (of biomass) used as a soil amendment to improve soils' water-holding capacity, nutrient availability and carbon stock Can be used as mitigation option with benefits for adaptation, but evidence suggests that it has greater potential in tropical regions	M

Table 4.1. Continued

Response category	Response option	Description/examples	Rating
Soil/land management for CO_2 removal	Enhanced weathering of minerals	A range of methods can be used to enhance weathering of naturally occurring minerals though their addition to soils as amendments in the form of minerals, crushed silicate rock, or volcanic ash Weathering generates alkalinity which results in the conversion of atmospheric CO_2 into dissolved inorganic carbon (carbonates). Inorganic carbon is removed via soil drainage and eventually results in long-term oceanic storage	L
	Bioenergy and bioenergy with carbon capture and storage (BECCS)	The use of bioenergy can mitigate climate change though the reduced use of fossil fuel-based energy. Bioenergy may be in the form of bioelectricity or biofuels BECCS is the combined use of bioenergy in conjunction with carbon capture and storage technologies Although BECCS features prominently in many future climate and socioeconomic scenarios, it has yet to be deployed at significant scale	H
Forest land management	Forest management	Encompasses a range of approaches to sustainable forest management. Carbon stock in biomass, litter and soil is enhanced while the timber products provided by the forest land are used to reduce emissions in other sectors through options including material substitution and energy generation Forest management that focuses solely on increasing timber biomass may have adverse impacts on biodiversity and resilience of the forest system to climate change	M
	Reduced deforestation and forest degradation	This suite of options form part of a major strategy to reduce global GHG emissions, with significant co-benefits for biodiversity, and is more cost-effective than afforestation or reforestation Requires control of the drivers, including overharvesting of forests, settlement or agricultural expansion, as well as a lack of governance and law enforcement to protect forest resources	L
	Reforestation and forest restoration	Reforestation is the conversion of land to forest that has previously been afforested but currently used for another purpose such as agriculture Forest restoration includes practices aimed at improving the ecological integrity of degraded forests Both approaches can result in increased carbon stored in forest biomass	L
	Afforestation	Refers to the conversion to forest of land that has historically not been forested Afforestation increases carbon stocks stored in biomass (above ground) with important co-benefits for land degradation, especially where it occurs on already degraded land There are complex interactions between large-scale afforestation and biophysical feedbacks to the climate system as well as potential trade-offs with food security and biodiversity	H
Other ecosystem land management	Fire management	A range of land management options aimed at "safeguarding life, property and resources through the prevention, detection, control, restriction and suppression of fire in forest and other vegetation" Examples include alternative forestry management for wildfire prevention and prescribed burning	M

Table 4.1. Continued

Response category	Response option	Description/examples	Rating
	Reduced landslides and natural hazards	Landslides and natural hazards are mainly initiated by a combination of human activity and climate events Management includes vegetation management such as afforestation or physical/engineering solutions such as dams, terraces and other soil stabilisation methods	M
	Reduced pollution including acidification	Management of air pollutants including particulate matter is beneficial for climate, human health and ecosystems One consequence of air pollution is acid deposition, which is a significant land degradation process. For example, the expansion and intensification of agriculture is associated with increased NH_4 emissions contributing to both acidification and eutrophication Preventative actions in agriculture include adding amendments to slurry to reduce NH_4 volatilisation Moving to renewable energy sources can reduce pollution from industrial, transport and heating systems	H
	Management of invasive species/encroachment	Invasive species represent a threat to ecosystem integrity, and particularly endangered local species. Management options include the clearance of invasive species and the introduction of natural enemies (biocontrol) Non-native species such as those used in plantation forestry (to meet demand for specific timber products) can have negative impacts on biodiversity and ecosystem functioning. Management options include inclusion of more mixed forestry (with native species) Encroachment of woody species on grassland/cropland causes significant land degradation with negative impacts on productivity and altered wildfire regimes. Options include alternative grazing management and clearance	L
	Restoration and reduced conversion of coastal wetlands	Involves a range of actions undertaken to avoid further conversion and restore degraded coastal wetlands including mangroves, salt marshes and seagrass ecosystems Can provide adaptation benefits through the provision of increase protection against coastal flooding and erosion associated with storm surges	L
	Restoration and reduced conversion of peatlands	Involves a range of actions undertaken to restore degraded peatlands and avoid further human conversion of peatland areas As well as potentially contributing to long-term mitigation by acting as a carbon sink, there are co-benefits for water quality and management, biodiversity conservation and adaptation to climate change. Note that site-specific constraints may affect the cost and effectiveness (in term of GHG emissions) of actions taken	H
	Biodiversity conservation	Refers to a range of land management and species-specific actions that may be taken to conserve and maintain biodiversity Examples include the establishment of protected areas, mapping and monitoring of biodiversity levels (repeated over time to investigate trends) and taking measures to restore lost habitats and species of concern Many options require active engagement with landowners through targeted policy measures aimed at retaining or restoring habitats or species of concern (e.g. agri-environmental schemes)	H

Descriptions are primarily adapted from Chapter 6 of the SRCCL (Smith *et al*., 2019), supplemented with information from Chapters 4 (Olsson *et al*., 2019), 5 (Mbow *et al*., 2019) and 7 (Hurlbert *et al*., 2019). Rating refers to the potential applicability of a response option to the land system in Ireland. The potential applicability is categorised as low (L), moderate (M) or high (H) according to the assessment summarised in Table A1.1.

et al., 2019). Globally this response option has a large climate change mitigation potential with significant co-benefits for the land-system primarily delivered through reductions in land use required to produce animal-sourced food (IPCC, 2019b).

Dietary change has been assessed as having high potential applicability to Ireland (Table 4.1). However, because available data and assessments that are specific to Ireland are limited, this assessment comes with relatively low confidence (Table A1.1). It has been estimated that in Ireland, over the period 2010–2017, protein available for human consumption amounted to 109.6 g per capita per day (FAOSTAT, 2017). This is substantially higher than the global average of 81.3 g protein per capita per day, but is similar to the EU average. Similarly, over the same period, the proportion of total available protein from animal as opposed to plant sources was around 58.6% in Ireland, compared with a global average of 39.5% (FAOSTAT, 2017). This suggests that there may be scope to reduce the level of animal-sourced protein in Irish diets. However, this is a complex issue since overall dietary composition must be considered and not just protein content and calorific value alone.

There are several key barriers and concerns in relation to dietary change, and the SRCCL recognised that there are strong local environmental, socioeconomic and cultural aspects to human diets (IPCC, 2019a). Allowing consumers to make informed food decisions requires foods to be labelled adequately and communication regarding the environmental impact of different foods. Furthermore, if lowering the GHG footprint of a food product results in additional cost to the consumer, this may be prohibitive particularly for poorer societal groups. It must be noted that, as the vast majority of ruminant-based food produced in Ireland is exported (DAFM, 2019), the impact of reduced intake of animal-sourced protein in Ireland may have a limited impact on the national GHG inventory. However, at the individual consumer level, reducing the intake of animal-sourced food, particularly that from ruminant livestock, could make a positive contribution towards reducing a personal GHG footprint. To fully understand the potential contribution that dietary change could make to national climate change mitigation in Ireland, a comprehensive national analysis would be required. This would also necessitate more detailed and large-scale data collection on actual dietary consumption along with up-to-date calculation of associated GHG footprints for food products.

4.2.2 Reduced food waste (consumer or retailer)

The reduction in food waste has high global mitigation potential, with large co-benefits for food security (Smith *et al.*, 2019), and has been assessed as being highly applicable to Ireland (Table 4.1). Food waste is primarily determined by consumer behaviour, whereas food loss occurs at the post-harvest stage and can largely be mitigated by technological deployment (Mbow *et al.*, 2019). The potential to positively impact climate change mitigation by reducing food loss is especially high in the case of food products that have a larger GHG footprint, such as animal-sourced foods. There may be potential to better link information campaigns on reducing food waste with environmental information regarding the environmental cost of specific foodstuffs.

In Ireland, food waste is a significant problem, amounting to an estimated 117 kg per household per year (DECC, 2020). This is estimated to cost each household between €400 and €1000 per year, and over 60% of the food waste can be classified as avoidable, e.g. leftovers, spoiled fruit and vegetables and out-of-date perishables. At an EU-27 level (i.e. before Croatia joined the EU), Ireland was found to be one of the four worst nations for food waste at household level, with around 42% of individuals wasting more than 5% of total food purchased (Secondi *et al.*, 2015). In 2017, daily available food calories in Ireland was estimated at 3717 kcal per capita, which is somewhat higher than the EU-28 average, and substantially higher than the world average (FAOSTAT, 2017). This value is also significantly higher than the recommend daily calorific intake for moderately active adults according to Food Safety Authority of Ireland (FSAI) guidelines (FSAI, 2017).[8] This indicates that there is a surplus of calories

8 The recommended daily calorie intake for moderately active average adults (19–50 years old) in Ireland is 2000–2200 and 2400–2800 calories for females and males, respectively. The estimate of required calorific intake varies depending on age, sex, body weight/size as well as exercise level, being lower than average for ‘sedentary’ adults and higher than average for those who are more active (FSAI, 2017).

at the national level that could be targeted in terms of food waste at the consumer level.[9] However, on a positive note, Ireland was also one of the fastest improving countries across the EU for reducing food waste between 2011 and 2013 (Secondi *et al*., 2015), which may indicate positive impacts from public information drives such as the "Stop Food Waste" campaign.[10]

4.3 Response Options Based on Land Management

Many of the land-based response options assessed in the SRCCL have the potential to make positive contributions to both climate change mitigation and adaptation (IPCC, 2019a). Central to achieving positive outcomes through the application of these response options is the overarching principle of sustainable land management. Sustainable land management is concerned with the stewardship of the land, including soil, water, forests, flora and fauna, to meet human needs but also ensure long-term productive potential and maintenance of ecosystem services (Olsson *et al*., 2019). Many key land degradation processes that are increasingly being exacerbated by climate change can be avoided, reduced or, in some cases, reversed through the application of sustainable land management practices (IPCC, 2019a). Under the land management category there are five subcategories of response options: agriculture, soil-based, soil/land management for CO_2 removal, forest management and other ecosystems.

4.3.1 Agriculture

The food system, including both its supply and demand sides, is a major contributor to global GHG emissions, accounting for between 21% and 37% of total GHG emissions over the period 2007–2016 (IPCC, 2019a). Climate change is already having a negative impact on global food security, changing precipitation patterns and resulting in temperature increases and a greater frequency of some extreme events (Mbow *et al*., 2019). Therefore, mitigation and adaptation in the agriculture system are vital, and most likely to be successful if implemented through a wider approach to sustainable land management. Many of the response options assessed here have a large potential to positively impact climate change mitigation and adaptation goals, as well as improve food security. Of the eight response options assessed under this category, five were found to have high potential applicability to Ireland: increased food productivity, improved grazing land management, improved livestock management, agroforestry and agricultural diversification.

Increased food productivity

This response option includes a range of actions across crop and livestock agriculture and therefore overlaps considerably with other integrated response options (assessment of specific actions is included in the relevant sections below). Improving efficiency in agricultural systems was a central goal of agricultural research and industry throughout the last century, during which time large gains in food productivity were achieved. A large portion of this success can be attributed to large global investment in crop research and infrastructure, as well as considerable market development that took place during the "Green Revolution" in the second half of the 20th century (Pingali, 2012). This approach is focused on the production of more agricultural outputs per unit input of land or resources, but global increases in food production have also been associated with increased human land use and intensification of land use (Arneth *et al*., 2019). Increased food productivity has been assessed as having the potential to make a large positive contribution to global mitigation and adaptation (Smith *et al*., 2019). However, for increased productivity to be sustainable in the long term it needs to occur within environmental and ecological limits (Haughey *et al*., 2019).

This response option has been assessed as having high applicability to Ireland, as it could be applied across all sectors of agricultural production (Table A1.1). However, it is likely that in some cases considerable gains in productivity have already been made, with the result that further returns in terms of contribution to climate change mitigation and adaptation may be limited. In any system there is a risk that improvements in efficiency will result in

9 This metric does not take into account how the availability of food supply is distributed across societal groups.

10 https://stopfoodwaste.ie/

rebound effects (Mbow *et al.*, 2019) (Figure 4.1). This is relevant in Ireland, where the agriculture sector, and in particular the dairy sector, has expanded production in the last decade. Despite significant gains in the production efficiency of dairy systems in Ireland over recent decades, between 2012 and 2016 there was an 8% increase in CH_4 emissions driven by a 38% increase in milk production over the same period (Lanigan *et al.*, 2018).

Improved grazing land management

This encompasses a range of measures aimed at reducing GHG emissions from grasslands as well increasing the amount of carbon sequestered in grassland soils. This option has been assessed as having moderate global adaptation and mitigation potential with significant co-benefits for reduced land degradation and enhanced resilience to extreme climate events such as drought (Mbow *et al.*, 2019). For example, avoidance of overgrazing through implementation of site-specific grazing management can reduce both soil degradation processes and associated carbon loss (Olsson *et al.*, 2019). Actions under this response option may be classed as applying either to vegetation management, including soil nutrition, or to livestock management as related to grazing management and stocking density. Despite the fact that many of the actions under improved grazing land management are cost negative or close to neutral, uptake by famers is often low.

Improved grassland management has been assessed as having high applicability for Ireland owing to the dominance of grassland-based agriculture (Table A1.1). It is recognised that there is considerable scope to improve the efficiency of grazing land management in Ireland. This includes increasing the production and utilisation of grass on farms, which are below optimum levels on most farms (O'Donovan *et al.*, 2018). Optimised management of livestock manure can also make a significant contribution to climate change mitigation through reductions in both CH_4 and N_2O emissions, with co-benefits for the environment (Mbow *et al.*, 2019). With respect to grassland management, this applies to the timing and method with which manure is applied to the land. Specific actions include the adoption of alternative technologies for spreading manure, such as the "trailing shoe" method, which reduces rates of nitrogen

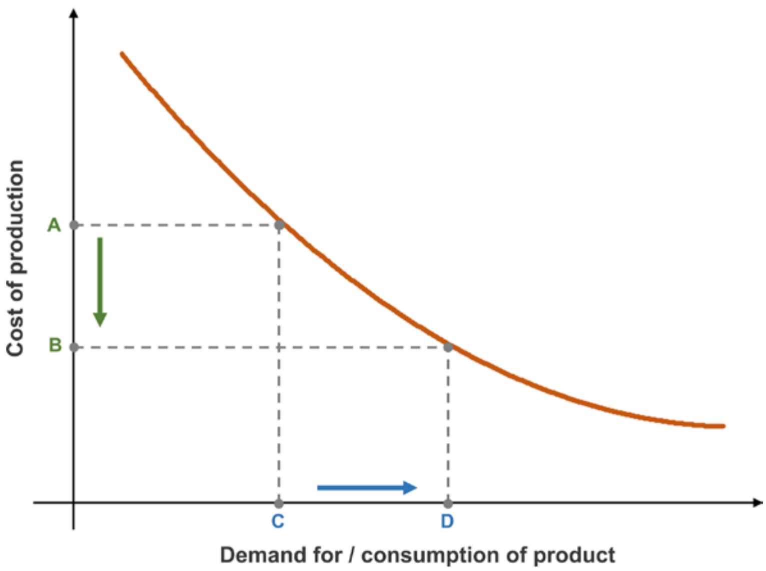


Figure 4.1. Illustration of the Jevons paradox or rebound effect, which is generally defined as a lower than expected reduction, or a net increase, in global resource use despite increases in resource use efficiency. The orange line illustrates a relationship between the cost of production and demand/ consumption for a product. As system efficiency increases, the cost of production decreases (A → B), also reducing the quantity of inputs required. However, the decrease in cost results in an increase in demand for the product (C → D). This increase in consumption drives higher levels of absolute production and resource use, negating the initially experienced environmental benefits of increased efficiency.

volatilisation and maximises nutrient use efficiency (Bourdin *et al*., 2014). In Ireland, low-emission slurry spreading has been estimated to have a mitigation potential of 0.117 Mt CO_2 eq. year^{-1} between 2021 and 2030 (Lanigan *et al*., 2018). However, there are significant socioeconomic barriers to the uptake of new manure application technologies, which may require novel knowledge transfer and policy solutions. There is also significant mitigation potential in optimisation of fertiliser formulations. According to the Teagasc 2018 marginal abatement cost curve (MACC) analysis for GHG reductions in Irish agriculture, altered fertiliser formulations represent the single largest agricultural abatement option, with a mean N_2O reduction potential of 0.52 Mt CO_2 eq. year^{-1} between 2021 and 2030 (Lanigan *et al*., 2018).

There are also co-benefits to the use of multispecies grasslands, including higher protein content of such swards, which can improve animal nutrition and reduce the need for concentrated animal feed, as well as providing increased resistance to weeds, which may reduce the need for herbicide application (Lüscher *et al*., 2014). Grazing trials in Ireland indicate that the performance of ewes and lambs is improved under multispecies grassland systems compared with perennial ryegrass monocultures (Grace *et al*., 2019). Multispecies grasslands also have the potential to play a role in climate change adaptation. There is growing evidence that swards which combine grass, legume and deep-rooting species have the potential to increase the resistance and resilience of grasslands to severe drought events (Hofer *et al*., 2016). Importantly, this can increase overall forage yield stability throughout the growing season, which is vital if grass utilisation is to be maximised across the year (Haughey *et al*., 2018). However, the persistence of clover in grassland swards as well as the need for significant knowledge transfer to farmers remain barriers to uptake (Grace *et al*., 2018; Lüscher *et al*., 2014). According to the Teagasc 2018 MACC, a 25% uptake of legumes by beef farmers and a 15% uptake by dairy farmers has the potential to reduce GHG emissions by 0.069 Mt CO_2 eq. year^{-1} between 2021 and 2030 (Lanigan *et al*., 2018).

Improved livestock management

This suite of actions is primarily targeted at reducing GHG emissions through efficiency gains and reduced CH_4 and N_2O emissions across livestock systems. Improved livestock management has been assessed as having moderate global mitigation and adaptation potential (Smith *et al*., 2019). Actions under this response option may be categorised as those focused on animal genetics and health (including fertility), animal diets and feed, or manure management during storage. Implementation of improved livestock management has the potential to provide significant co-benefits for global food security (Mbow *et al*., 2019). Unlike actions focused on increased carbon sequestration in soils, livestock management is not limited by carbon sink saturation and there is a relatively low risk of carbon sink reversal. However, since this suite of actions is primarily based on increased efficiency, there are associated risks of rebound effects occurring (Mbow *et al*., 2019). Improved livestock genetics and fertility can significantly improve the efficiency of livestock production systems. Many of these options focus on improving the efficiency with which livestock convert feed into animal products, while others reduce the amount of time taken for an animal to reach its productive potential and hence reduce the amount of time for which the animal is housed and fed. This has the potential to reduce the GHG emissions per unit of product produced or emissions intensity associated with production.

This response option has been assessed as having high applicability in Ireland (Table A1.1). It is recognised that there is significant scope to support climate change mitigation through improved livestock genetics and associated increased production efficiency. Improved animal health in dairy and beef systems in Ireland has the potential to increase production efficiency and deliver a GHG mitigation of 0.131 Mt CO_2 eq. year^{-1} (Lanigan *et al*., 2018). This mitigation would be delivered if 20% of the national herd changed from baseline or current health to healthy status. Optimising the health of livestock is particularly important in the context of adaptation, as climate change and extreme events are likely to negatively affect animal health. Improvement in the genetics of the national dairy herd (based on the economic breeding index) has been estimated to have a mitigation potential of 0.43 Mt CO_2 eq. year^{-1} (Lanigan *et al*., 2018). This mitigation potential is delivered through improved animal health and survival, reduced animal culling and replacement, and earlier calving, all of which contribute to improved efficiency. In the beef sector, genetic improvements have the potential to significantly increase the "liveweight gain" of cattle by increasing the efficiency with which feed is utilised. This improvement reduces the time taken for an animal to reach production and results in a reduction in the GHG emissions per unit of protein produced. The 2018 Teagasc MACC estimated that these genetic improvements in the beef sector could deliver GHG mitigation of 0.061 Mt CO_2 eq. $year^{-1}$, and do so in a cost-negative manner at farm level (Lanigan *et al*., 2018). However, absolute reductions in GHG emissions from beef production would be achieved only in the absence of rebound effects, and in practice this requires overall production to be limited.

Agroforestry

The potential of agroforestry to contribute to addressing the land challenges assessed in the SRCCL is highly significant (Smith *et al*., 2019). Implementation of agroforestry has the potential to make a large positive contribution to climate change mitigation and adaptation, tackling desertification and land degradation as well as enhancing food security (Smith *et al*., 2019). In practice, the term "agroforestry" covers a diverse set of land use systems where woody perennials are planted on the same land as agricultural crops or livestock (Table 4.1). This combined use of land for crops or livestock with trees that may provide timber, fibre or food is an example of land sharing, where multiple products and ecosystems services are provided from the same unit of land (Haughey *et al*., 2019). Agroforestry has the potential to contribute to improved food productivity while simultaneously enhancing biodiversity and supporting climate change adaptation of food production systems (Mbow *et al*., 2014, 2019). As a key response option under the umbrella of sustainable land management, agroforestry has significantly greater potential to deliver co-benefits in terms of reduced land degradation and the provision of additional ecosystem services than land under conventional agricultural management (Olsson *et al*., 2019).

Agroforestry has been assessed as highly relevant to the land system in Ireland since it could be applied to several major agricultural sectors, including livestock, cropland and horticulture, with overlaps with the forestry sector (Table A1.1). Silvopasture is a form of agroforestry that combines trees with grassland and grazing livestock and is particularly relevant for livestock farming systems in humid temperate regions such as Ireland (McAdam, 2018). Compared with regular grasslands, silvopasture systems have the potential to provide a more diverse set of outputs, including timber, fruit and biomass for fuel and energy generation, with co-benefits for carbon sequestration. Other key benefits include improved soil–water dynamics that give rise to reduced water run-off and increased animal trafficability under rainfall extremes (McAdam, 2018). This has co-benefits for climate adaptation and may aid sustainable intensification through the potential for extended grazing seasons and increased grass utilisation.

However, despite the many benefits of agroforestry, global uptake remains relatively low (Olsson *et al*., 2019). There are many possible barriers to uptake, including the cost of establishment, the need for knowledge transfer and market access with regard to additional agricultural or timber-based products. The perception of risks associated with adopting agroforestry as well as the time taken for return on investment in the case of timber or tree crops have been identified as important. In Ireland, a silvopasture based agroforestry scheme including an establishment payment and annual premium payments for a period of 5 years was available under the DAFM 2014–2020 Rural Development Plan. However, despite the significant grant aid available, up to €9520 ha^{-1} over 5 years (Teagasc, 2020), uptake by farmers was very low. Nationally, as of 2018, under 47 ha of agroforestry was undergoing the process for approval under the DAFM agroforestry scheme (McAdam, 2018). This report recommends that a review of the barriers to the uptake of agroforestry systems in Ireland, especially in relation to current agri-environmental schemes, is undertaken.

Agricultural diversification

This is a wide-ranging response option that includes actions which seek to increase the resilience of farms, farm households and rural communities to climate change and economic risks. Primarily targeted at increasing resilience, agricultural diversification has been assessed as having low global mitigation but high global adaptation potential (Smith *et al*., 2019). However, it is possible that actions taken under this broad category may also promote increased storage of carbon in soils and biomass (e.g. agroforestry) or offset the use of fossil fuels (e.g. bioenergy crops). This response option is different from livelihood diversification (see Table 4.1), as it applies specifically to diversified agricultural production and therefore does not include off-farm employment or participation in the tourism sector, for example. Agricultural diversification can also form part of the approach to achieve sustainable intensification through farming system redesign (Pretty *et al*., 2018). Examples of such agricultural system redesign include the implementation of alternative farming systems such as organic farming, agroforestry or intercropping (Haughey *et al*., 2019). Agricultural diversification may also include planting commercial forestry on existing farmland, which provides an additional farm income stream.

Globally, significant barriers to the uptake of diversified agriculture have been identified (Smith *et al*., 2019). These include required investment in new farming systems or lack of enabling conditions in terms of access to or development of new markets, or restrictive agricultural policies. In general, the farming community in Ireland has been reluctant to diversify its enterprises, preferring to focus on conventional production practices and on a small number of outputs (Moroney *et al*., 2016). In a survey of farmer attitudes towards diversification in Ireland, Meredith *et al*. (2015) found that only a small proportion of famers were actively interested in diversifying their farming system. When asked about the preferred farm development route, 58% preferred a model combining current farming practices with off-farm work (livelihood diversification), 38% preferred expansion of the current farming system (without diversification) and only 2% preferred a diversified farm business. However, the study did not find that farmers were ideologically opposed to agricultural diversification, only that it was simply not their preferred option. Clearly there are significant challenges to agricultural diversification in Ireland, and this report recommends that a review of these barriers is conducted.

4.3.2 Soil-based land management

Response options in this category seek to utilise soil management to protect and enhance soil health with significant potential to aid climate change mitigation and adaptation as well as tackling land degradation (Smith *et al*., 2019). The sustainable management of soils should ensure that current soil carbon stocks are protected and, if possible, enhanced through increased carbon sequestration. Managing soil for increased carbon content has important synergistic effects on soil water and nutrient retention, which can, in turn, benefit agricultural productivity (Mbow *et al*., 2019). Sustainable management of soil has important benefits for overall soil health and reduces the occurrence or severity of degradation processes such as soil erosion, soil compaction and soil salinisation (Olsson *et al*., 2019). The potential to use soil amendments such as biochar and the process of enhanced mineral weathering in agricultural soils to enhance carbon storage and CO_2 removal has also been considered here (Table 4.1). Note that in the case of biochar there is the potential for negative effects on food security depending on the sustainability of feedstock and scale of deployment (Smith *et al*., 2019). Note that for response options in this category, there are significant knowledge gaps regarding the potential contributions of soil-based land management to climate change mitigation and adaptation. None of the five response options assessed under soil-based land management was assessed as having high potential applicability to Ireland (Table 4.1).

4.3.3 Forestry and bioenergy

The integrated response options in this category focus on delivering mitigation as part of a sustainable land management approach. Land management for forestry and bioenergy has the potential to make a large contribution to climate change mitigation (Smith *et al*., 2019). Sustainable forest management is vital to ensure the long-term viability of forest land to provide a wide range of ecosystem services as well as timber, fibre and feedstock for bioenergy. When implemented sustainably, many of these options have co-benefits for adaptation, as well as reducing land degradation pressures and providing many other ecosystem services, such as space for biodiversity and maintenance of water quality (Olsson *et al*., 2019). However, in the case of some forestry and bioenergy-based response options there is a risk that implementation on a large scale will result in increased competition for land with significant negative impacts on food security and other ecosystem services (Hurlbert *et al*., 2019). In an Irish context, response options such as afforestation and bioenergy crops have large potential to contribute to climate change mitigation goals and are relatively established practices, meaning that they could be deployed in the near term (Lanigan *et al*., 2018; McGeever *et al*., 2019). Of the four options assessed under forestry management, only afforestation was found to have high potential applicability to Ireland. Of the two options assessed under land management for CO_2 removal, only bioenergy was found to have high potential applicability to Ireland.

Afforestation

Increasing the area of global forestry on lands which are not currently forested is seen as one of the ways in which the land system can contribute significantly to climate change mitigation. The SRCCL assessed afforestation as having the potential to make a large positive contribution to both mitigation and adaptation (Smith *et al*., 2019). When afforestation occurs on appropriate lands and is implemented and managed in a sustainable manner, it has the potential to contribute to reducing land degradation and desertification globally (IPCC, 2019a). As part of the SRCCL assessment of global land use change under different Shared Socioeconomic Pathways (SSPs) and the global warming Representative Concentration Pathway (RCP) 1.9, increasing the area of forest is important across all assessed SSPs (where this warming level is feasible). The change in forest area compared with a 2010 baseline 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 (SRCCL, Figure SPM.4; IPCC, 2019a). Levels of increased forestry required under "middle of the road" (SSP2) and "resource-intensive" (SSP5) pathways were also very large but are associated with different trade-offs.

Such large increases in the levels of global afforestation pose major challenges to sustainability and, if implemented at very large scales, would pose significant risks to global food security. In this case, food security risks are primarily due to increased land competition, although there are also considerable risks to biodiversity, especially where fast-growing non-native tree species dominate afforested land (Smith *et al*., 2019). Yet, it is also recognised that relatively large-scale afforestation can be implemented sustainably (IPCC, 2019a). This relies on integration with other land uses to ensure that food security is not negatively affected and afforestation works best in the case of lands that are already degraded or are generally less suitable for conventional agriculture.

Afforestation has been assessed as having high potential applicability to Ireland (Table 4.1). As forestry cover in Ireland is relatively low by comparison with average European levels, there is significant scope to increase overall forest cover (section 2.5). Consequently, increasing the area of forestry in Ireland is a central component of the national climate change mitigation plans. The government of Ireland has set ambitious targets to increase forestry to 18% of total land cover by 2046 (DAFM, 2015b). It has been estimated that this would mean 490,000 ha of additional forest area (Lanigan *et al*., 2018), which is equivalent to an afforestation rate of around 15,300 ha^{-1} $year^{-1}$ over the period 2014–2042. However, there is significant reluctance among landowners to convert agricultural land to forestry. As a result, Lanigan *et al*. (2018) considered an afforestation rate of 7000 ha^{-1} $year^{-1}$ to a more realistic target and estimated that this could still achieve a significant mitigation of 2.1 Mt CO_2 eq. $year^{-1}$.

Just as there are challenges associated with sustainably increasing forestry globally, there are significant concerns in Ireland. A sustainably focused afforestation programme, to avoid negative impacts, needs to consider soil carbon, water quality, biodiversity and society more generally. Historically, this has not been the case in Ireland. For example, the significant afforestation on organic soils that took place in the 1990s has proved to have a negative impact on timber quality (section 2.4), and accompanying drainage activities are likely to have resulted in significant soil carbon loss. It has been suggested that the most pragmatic approach to afforestation in Ireland would be to focus planting on so-called "marginal grassland" soils and "marginal farming systems" (Farrelly and Gallagher, 2015). The area of marginal grassland has been estimated at 1.3 million ha, which would provide a significant area for afforestation. By targeting afforestation at marginal grassland, more productive agricultural land, such as cropland, would be preserved for food and feed production. However, the focus on marginal grassland for afforestation in Ireland poses specific challenges for sustainability, the environment and society. The soil type in any proposed area of afforestation would need to be carefully considered, as drainage for planting could result in soil carbon loss and poor-quality timber outputs. Forestry governance and policy in Ireland has historically led to conflict between stakeholders such as environmental groups and non-governmental organisations and stakeholders such as landowners and forestry companies. These disagreements often arise because of conflicting expectations regarding the services forestry is expected to deliver (Bonsu *et al*., 2019). For example, some stakeholders traditionally prioritise commercial outputs whereas others prioritise broader ecosystem services such as carbon sequestration and biodiversity conservation. Therefore, targeting afforestation at specific regions requires careful integration with current land use and ecosystem services and would benefit from a landscape approach that actively engages multiple stakeholders.

Bioenergy and BECCS

Like afforestation, bioenergy and bioenergy coupled with carbon capture and storage (BECCS) technology form an important part of the global mitigation potential of the land system. The potential of bioenergy to contribute to global mitigation is greatest where it is coupled with carbon capture and storage (CCS). CCS is not assessed in detail in this report, although it is important to note that this technology has not yet been deployed at scale and requires significant further technological development (Fridahl and Lehtveer, 2018). In terms of land use required, the deployment of bioenergy is expected to rival that of afforestation under the SSPs assessed in SRCCL provided global warming is limited to levels consistent with RCP1.9 (SRCCL, Figure SPM.4; IPCC, 2019a). Notably however, towards the end of the century, bioenergy plays a smaller role in land use under a "sustainability focused" (SSP1) pathway than under a "resource-intensive" (SSP5) pathway. This difference between SSPs reflects significant concerns regarding the sustainability of such large-scale global deployment of bioenergy (Smith *et al*., 2019). Where applied at large scale, bioenergy and BECCS have been assessed as having a significant potential to contribute to global mitigation efforts, but with likely negative impacts on adaptation. Negative impacts of large-scale deployment of bioenergy (with or without CCS) are expected to significantly increase competition for land and water resources, resulting in increased food security risks as well as land degradation pressures (Hurlbert *et al*., 2019).

Bioenergy has been assessed as having high potential applicability to Ireland (Table 4.1). However, there is significant uncertainty regarding this assessment since the type of bioenergy used and future potential of CCS affect this high-level analysis. Where applied primarily to cropland, the area available for bioenergy crops is expected to be limited by food and animal feed security constraints. However, where applied to grasslands (marginal grasslands in particular), there could be considerable scope to deploy bioenergy at scale. In the 2018 Teagasc MACC analysis, a wide range of bioenergy options for Ireland were assessed (Lanigan *et al*., 2018). Combined, the options considered, which include those based on biomass, anaerobic digestion and biofuels, have the potential to provide mitigation of 1.702 Mt CO_2 eq. year^{-1}. Most of this mitigation potential is provided by 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. The use of willow biomass as feedstock for electricity generation in stations that currently use peat would significantly reduce infrastructure costs. In this analysis, use of willow and miscanthus for biomass production is focused on grassland and specifically low intensity beef farming.

The anaerobic digestion of grass can be used to produce biogas (around 55% CH_4), which can further be refined to biomethane (around 97% CH_4), which, in terms of CH_4 content, is equivalent to natural gas and can provide a renewable source energy across a wide range of sectors. The use of harvested forage from grasslands as feedstock for aerobic digestion is recognised as having a particularly large potential in Ireland owing to the combination of the dominance of pasture land, favourable climatic conditions, avoidance of soil tillage (and associated carbon loss) and 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. 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.

The mitigation potential of anaerobic digestion for the production of biogas/biomethane for use in combined heat and power plants together with biomethane as a substitute for natural gas has been estimated at 0.374 Mt CO_2 eq. year^{-1} (Lanigan *et al*., 2018). Like the use of biomass as a replacement for peat in energy generation, the use of biomethane as a natural gas substitute is associated with a 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 of biogas to produce biomethane. As noted by Meehan *et al*. (2017), if the feedstock for anaerobic digestion was sourced from marginal grasslands, negative effects on food production could be minimised.

4.3.4 Other ecosystems

Integrated response options in this category are focused on land management across natural and seminatural landscapes. Several of the assessed options have the potential to impact significantly on global climate mitigation and adaptation goals, but in many cases there is a high level of uncertainty regarding estimated potentials owing to a lack of global data (Smith *et al*., 2019). Most of these options have considerable co-benefits across a wide range of ecosystem services, such as carbon sequestration and storage, air and water quality, and biodiversity conservation. Several of the response options address specific hazards, such as wildfire, landslides or the management of invasive species, that are likely to be exacerbated by climate change and pose significant risks to both human and natural systems (IPCC, 2019a). Of the seven options assessed under the management of other ecosystems, three were found to have high applicability to Ireland: reduced pollution including acidification, restoration and reduced conversion of peatlands, and biodiversity conservation.

Reduced pollution including acidification

Improved management of air pollutants has benefits for climate, human health, and ecosystems. Globally, this response option has been assessed as having moderate adaptation potential, but the impact on mitigation is variable (Smith *et al*., 2019). A major negative consequence of air pollution is acid deposition, a process of land degradation that can negatively impact ecosystem function and biodiversity. Soil acidification in agricultural land is increasingly driven by excessive use of nitrogen fertilisers and, to a lesser extent, cation depletion through crop and forage offtake (Olsson *et al*., 2019). Excessive fertilisation with nitrogen and/or phosphorus can lead to eutrophication of waterways, which can significantly impact aquatic ecosystems and reduce water quality. The management of air pollutants can have positive impacts on food production. For example, reducing output of black carbon and ozone emissions can positively impact crop production (Mbow *et al*., 2019). Ammonia volatilisation resulting from the application to soils of organic (livestock manure/slurry) and synthetic fertiliser is a major global pathway for nitrogen loss from agricultural systems (Pan *et al*., 2016). Volatilised ammonia enters the atmosphere, where it may be transported considerable distances and results in the deposition of secondary pollutants, causing significant disturbance to the biogeochemical cycling of nitrogen globally (Fowler *et al*., 2013). Over 40% of applied synthetic nitrogen fertiliser can be lost through volatilisation, constituting a key component in driving indirect N_2O emissions from agriculture (Pan *et al*., 2016).

Based on its applicability to a wide range of agriculture production systems, this response option has been assessed as having high potential applicability to the land system in Ireland (Table 4.1). Excessive nutrient loading on agricultural soils is a key driver of eutrophication of waterways in Ireland (EPA, 2019). Where such pollution occurs, it represents an example of unsustainable intensification of agriculture that is both environmentally damaging and economically inefficient in terms of input costs. According to the National Submission on Air Pollutant Emissions in Ireland 1990–2018 to the United Nations Economic Commission for Europe (UNECE), ammonia emissions in Ireland increased by 7.9% between 1990 and 2018 (EPA, 2020b). Therefore, reducing ammonia emissions in Ireland is particularly important owing to the direct damaging effect of ammonia on ecosystem functioning and indirect effects through N_2O emissions. Ammonia emissions are primarily driven by agriculture, with livestock manure management being the main contributor. Similar to N_2O emissions, this route of nitrogen loss is largely dictated by livestock numbers, with increased use of inorganic nitrogen fertiliser also an important contributor.

Options to reduce pollution can involve a wide variety of sustainably focused measures ranging from increased efficiency in agricultural production to farming system change to reduce pressures. For example, particulate matter production, which is associated with the combustion of fossil fuels, can be reduced by moving to renewable sources of energy (Smith *et al*., 2019). In terms of land use, integrated nutrient management in agriculture is vital for reductions in eutrophication of waterways, soil acidification and ammonia emissions. Specific technologies can be deployed to reduce ammonia volatilisation from manures and fertilisers. Ammonia emissions from inorganic fertilisers can be significantly reduced through the use of non-urea-based formulations, precision/deep placement of fertiliser and the addition of amendments (Pan *et al*., 2016). The acidification or addition of other amendments to animal manure during storage has been shown to significantly reduce ammonia emissions (Kavanagh *et al*., 2019). However, the use of such amendments or alternative fertiliser technologies will come at a cost to farmers. To increase uptake of these options, specific incentives or other policy options may be required.

Restoration and reduced conversion of peatlands

This response option has been assessed as having moderate global potential to contribute to mitigation (Smith *et al*., 2019). However, it is likely to have a higher impact in regions with a high proportion of peatland cover, such as Ireland (Figure 2.1). Peatlands are particularly sensitive to changes in hydrology and vegetation cover, which makes these ecosystems vulnerable to land degradation and climate change pressures (Olsson *et al*., 2019). Peatlands are highly significant in terms of the carbon storage they provide globally, and their degradation represents a threat to that global carbon stock (Olsson *et al*., 2019). Importantly, and unlike most ecosystems, functioning peatlands can continue to sequester carbon for thousands of years.

This response option has been assessed as having high potential applicability to Ireland (Table 4.1). Ireland has a relatively large area of peatland cover, but a high level of peatland extraction for various human uses has resulted in overall high levels of degradation. It is estimated that, of the approximately 975,087 ha of peatland land cover in Ireland (CORINE, 2018), only 15% remains near-intact and in fully functioning condition (Wilson *et al*., 2013). It has been demonstrated that restoration of a blanket peatland in the west of Ireland which was previously used for peat extraction resulted in the creation of a net GHG sink (Wilson *et al*., 2016). Peatlands also represent important areas for biodiversity conservation and, indeed, most of the remaining intact peatlands are already designed as Special Areas of Conservation. Restoration of peatlands could also have significant co-benefits for improved water quality, in some cases reducing the cost associated with water treatment (for drinking water) and improved flood management. However, large-scale restoration would involve displacement of current uses of peatland for industrial and domestic extraction for fuel and energy as well as extraction for compost. Therefore, the restoration of the degraded peatland in Ireland represents a major opportunity but also a considerable challenge in terms of implementation.

Organic soils under agricultural management, primarily grassland, are estimated to cover around 300,000 ha in Ireland (section 2.4). This area is associated with a large contribution to the GHG emissions from soils, although there is a high degree of uncertainty regarding estimated values. Reducing emissions through alternative land management of organic soils under agriculture represents a significant opportunity to positively impact climate mitigation. In its 2018 MACC analysis, Teagasc estimated that water table manipulation of 40,000 ha of organic grassland soils could deliver mitigation of 0.44 Mt CO_2 eq. year^{-1} (Lanigan *et al*., 2018). Water table manipulations in this case refers to stopping current drainage of this area and restoring the water table to pre-drainage levels. However, implementation of this change in land management would have considerable cost, as well as a cost to farmers in terms of potentially reduced productivity.

Biodiversity conservation

Approximately 25% of the animal and plant species assessed as part of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment on Biodiversity and Ecosystem Services were found to be threatened and at risk of extinction unless action is taken to reduce the drivers of species loss (IPBES, 2019). Of particular concern is the degradation of global biodiversity hotspots, which constitute around 15% of the total ice-free land area (Smith *et al*., 2019). Globally, the diversity of local crop varieties and livestock breeds has also declined significantly as a result of the intensification of agriculture and reliance on an increasingly limited number of species for the supply of agricultural products (IPBES, 2019). This represents a loss of genetic diversity from the food system that may undermine resistance to pests and disease as well as potentially reduce resilience to climate change. This response option has been assessed as having moderate global potential to contribute to climate change mitigation and adaptation. In some cases, the protection of biodiversity can be synergistic with the protection of carbon stocks stored in soils and biomass. However, the interaction between biodiversity conservation and carbon cycling is highly complex, and positive interactions are not universal. Implementation of conservation measures can have strong co-benefits for food security by, for example, providing services such as insect-based pollination of crops and fruit. Where conservation measures reduce the land area available for food production, negative impacts on food security are possible owing to increased competition for land.

Biodiversity conservation has been assessed as having high potential applicability to Ireland (Table 4.1). In 2019, climate change was identified as a “pressure” for many of the habitats assessed by the National Parks and Wildlife Service, indicating the need for coordination between climate change and biodiversity or conservation research programmes to quantify risks and assess adaptation options (NPWS, 2019). Coordination between climate mitigation strategies, particularly land-based options such as afforestation or bioenergy crops, and conservation strategies is required as part of overall land use planning. In conclusion, biodiversity conservation and climate change mitigation and adaptation policies and on-going research could benefit from more integration, a need highlighted by a recent report from The All-Island Climate and Biodiversity Research Network (Thorne *et al*., 2020).

4.4 Summary Response Option Potential

Many of the assessed response options can contribute positively to climate change mitigation and adaptation with co-benefits across the other land challenges (Smith *et al*., 2019). Importantly, the majority of the options are at advanced technological readiness levels, and many could be deployed at relatively low cost (IPCC, 2019a). However, there are several key caveats that need to be considered. Firstly, the application of the response options needs to be conducted in the context of sustainable development and sustainable land management (Hurlbert *et al*., 2019). This requires taking local environmental and socioeconomic conditions into account. Secondly, land is a limited resource, and neither the response options based on land management nor their contributions to the land challenges are additive (Smith *et al*., 2019). This means that, in some cases, land-based response options may compete for available land resources. Thirdly, the scale of deployment of some response options is a cause for concern due to potential negative consequences for land degradation, food security and biodiversity. This is particularly acute in relation to the deployment of afforestation and bioenergy crops at large scales (SRCCL, Figure SPM.3B; IPCC, 2019a).

Of the 40 integrated response options, 12 options were found to be highly applicable to Ireland, 15 to be moderately applicable and 13 to have low applicability (Table 4.1). Note that the assessment of some options’ relevance to Ireland was limited by a lack of data, particularly with regards to potential for climate change adaptation (Table A1.1). A lack of data also limited the assessment of potential climate change impacts on the functioning of the land system in Ireland, and a detailed assessment of these risks is recommended.

The twelve options with high applicability to Ireland are summarised in Table 4.2. Importantly, many of these relevant options are at an advanced state of technological readiness and could be deployed in the near term. However, despite the potential for deployment, this report has identified several options which currently have very low levels of uptake and further investigation is recommend so as to better inform policy.

Table 4.2. Integrated response options assessed as having the highest applicability to Ireland

Response option category	Response option	Notes/caveats
Demand management	Dietary change	Current deployment levels are not known. There are boundary issues with regard to exported and imported food and the associated production emissions
	Reduced food waste	National initiatives are under way, but food waste remains high
Agricultural land management	Increased food productivity	There are existing national research initiatives targeted at increased agricultural efficiency. There is a risk of rebound effects
	Improved grazing land management	There are significant opportunities for climate mitigation and adaptation, as this grazing is the largest type of national land use
	Improved livestock management	Can improve economic and environmental sustainability of livestock production. Actions under this option are efficiency based and associated with a high risk of rebound effects
	Agroforestry	Strong potential to achieve mitigation and adaptation goals with benefits for rural livelihood diversification. Current low levels of deployment indicate significant challenges to increased uptake by farmers
	Agricultural diversification	Low levels of deployment currently indicate a significant knowledge transfer challenge
Land management for CO_2 removal	Bioenergy and BECCS	Could make a significant contribution to climate mitigation but current low levels of deployment require coordinated actions. Sustainable deployment is required otherwise this option could negatively impact biodiversity and increase demand for land
Forest management	Afforestation	Sustainable deployment and forestry management required or can negatively impact biodiversity. Could increase competition for land and may face significant social resistance
Other ecosystems land management	Reduced pollution including acidification	Significant co-benefits for air and water quality, biodiversity conservation and reducing land degradation
	Restoration and reduced conversion of peatlands	Major potential to reduce GHG emissions and create carbon sinks in degraded peatlands and organic soils under agriculture
	Biodiversity conservation	Would benefit from more integration with climate change mitigation and adaptation policies. Land-based mitigation options could pose a threat to biodiversity conservation

5 Recommendations – Summary for Policymakers

5.1 Key Messages from Chapter 2: Land Use, Cover and Outputs

- Land use and cover in Ireland is dominated by grassland, which accounted for 61.0% of land use in 2016, while there is a relatively low level of forestry (10.7%) and cropland (9.5%) (Figure 2.1).
- Economically, agricultural outputs in Ireland are dominated by dairy and beef production. Other important outputs include pigs, cereals (barley, wheat and oats), sheep, poultry, potatoes and mushrooms (Table 2.1).
- Within the agriculture sector there is considerable variation in the intensity of land use between farming systems. Of the grassland-based livestock systems in Ireland, dairy farming is the most intensive in terms of inputs and stocking density, while beef and sheep farming are generally less intensive (Table 2.1).
- The wetland category, which is dominated by peatlands, accounts for a significant proportion of the land area in Ireland, at 16.1% (Figure 2.1). Peatlands have significant value in terms of carbon storage and other ecosystem services but have been largely degraded by human use (section 2.4).
- Forestry increased significantly in the last century; however, the rate of afforestation has dropped in recent decades. Commercial forestry is dominated by monoculture plantations of conifer species, but the area of native woodland planted has increased in the last decade (section 2.5).
- Ireland does not currently have a national land use map, which limits the potential for regional analyses of land use and intensity, which, in turn, affects our understanding of land–climate interactions.

5.2 Key Messages from Chapter 3: Greenhouse Gas Fluxes in Terrestrial Systems

- Owing to the dominance of ruminant livestock production and a low level of heavy industry, the GHG emissions profile in Ireland is markedly different to the EU-28 average. Between 2010 and 2017 agriculture accounted for 28.8% of GHG emissions in Ireland, compared with only 10.3% in the EU-28 over the same period (section 3.2). In addition, the LULUCF sector is a net GHG source in Ireland but a significant GHG sink in the EU-28.
- In the agriculture sector the main contributors to estimated GHG emissions in Ireland are CH_4 from ruminant livestock and N_2O from agricultural soils (Figure 3.1).
- Emissions in the form of N_2O from agriculture are primarily driven by inorganic nitrogen fertiliser use and the management of livestock manure. Increases in N_2O emissions from agricultural soils since 2011 have been driven by the intensification of production systems (section 3.2.2).
- Emissions of CH_4 attributable to ruminant livestock are dominated by emissions from dairy and beef cattle. Despite improvements in production efficiency, CH_4 emissions from livestock have increased in the last decade and closely track the size of the national herd (section 3.2.3).
- In the LULUCF sector, net GHG emissions in Ireland are driven by emissions from grassland, cropland and wetland, while forestry acts as a significant net GHG sink (section 3.3).
- Forestry is a significant carbon sink in Ireland (section 3.3.1); however, reduced rates of afforestation could reduce the rate of carbon sequestration over the coming decades. Soil carbon makes up the largest stock of carbon in forest land, but there is much uncertainty regarding trends in this pool, and further investigation is recommended (section 3.3.1).
- Estimated to account for 75% or total soil carbon in Ireland, peatlands represent a highly significant carbon stock (section 3.3.1). However, owing to their degraded state, these lands are a significant source of GHG emissions, with only a small fraction of the historic peatland area now in an ecologically intact state. However, there remains relatively high uncertainty in terms of site-specific functionality of peatlands and their associated GHG balances.

5.3 Key Messages from Chapter 4: Integrated Response Options

- The relevance of 40 integrated response options to the land system in Ireland was assessed, and 12 options were found to be highly applicable, many of which are at an advanced state of technological readiness (Table 4.2).
- Under the value chain management category, both dietary change and reduced food waste were found to be highly relevant to Ireland. These options have the potential to reduce GHG emissions on the demand side of the food system, particularly at an individual consumer level (section 4.2). Note that the assessment of the potential impact of dietary change and reduced food waste was limited by a lack of specific data for Ireland.
- Increased food productivity, improved grazing land and improved livestock management were found to be highly applicable to Ireland (Table 4.2). However, as these options are focused primarily on increased efficiency of production systems, to achieve absolute reductions in GHG emissions, rebound effects should be carefully considered, especially in the case of ruminant livestock-based agriculture (section 4.3.1).
- Agroforestry and agricultural diversification have significant potential to positively affect climate adaptation on farms as well as to contribute to mitigation and the economic resilience of farms. However, both options currently have low levels of deployment in Ireland and there are likely to be significant barriers to uptake (section 4.3.1).
- Afforestation and bioenergy deployment have been assessed as having large potential for a positive impact on national climate mitigation targets. However, both options face environmental and ecological constraints and can increase the demand for land. Therefore, large-scale deployment should be carefully integrated into broader land use planning (section 4.3.3).
- Improved management and restoration of peatlands and organic soils under agriculture represent a significant opportunity to reduce GHG emissions and, in some cases, create carbon sinks (section 4.3.4). However, restoration activity entails significant investment and there are likely to be social barriers to its acceptance where peat extraction continues for industrial and household use. In addition, it is likely to take time for restoration activity to achieve a reduction in GHG emissions.
- Biodiversity conservation goals may benefit from increased integration with climate change adaptation and mitigation research and policy actions (section 4.3.4). There is also considerable uncertainty regarding the potential impact of climate change on biodiversity in Ireland.
- Different expectations among stakeholders of the services and outputs that land should provide can lead to conflict. There is scope to increase the effectiveness of land-based mitigation options such as afforestation, bioenergy and peatland restoration, provided that all local stakeholders are actively engaged in the planning and deployment processes.

5.4 Concluding Comments and Recommendations

- Taking account of the current distribution of land use and land use intensity in national land use planning strategies could help maximise synergies between policies across different sectors of the land system. This would be significantly aided by a publicly available national land use map.
- Despite their impact on the national GHG footprint, there is considerable uncertainty regarding the current functional status of peatlands and organic soils under agricultural management in Ireland. Urgent data collection and analysis is recommended to address this knowledge gap.
- Further data collection and analysis of the potential impact of dietary change and reduced food waste on climate mitigation and adaptation is recommended. This work should also consider carbon leakage related to exported food products from Ireland.
- Several of the land-based response options with high potential in Ireland, such as agroforestry and agricultural diversification, have very low levels of uptake. A review of the effectiveness of current policies targeting their deployment is recommended to better inform policy.
- In the case of the response options that require additional land, careful consideration should be given to maintaining current carbon sinks, as well as biodiversity and water quality. This can

be aided by the application of a sustainable land management approach to land use.

- Several of the high-potential options require investment in new technologies (e.g. agricultural machinery) and infrastructure (e.g. bioenergy processing); this may be a barrier to uptake, but this can be overcome, at least partly, through coordinated local and government-level actions.
- Many of the response options assessed as having high applicability to Ireland could be readily deployed in the near term with significant potential to aid climate adaptation and mitigation goals.

References

Acs, S., Hanley, N., Dallimer, M., Gaston, K.J., Robertson, P., Wilson, P. and Armsworth, P.R., 2010. The effect of decoupling on marginal agricultural systems: implications for farm incomes, land use and upland ecology. *Land Use Policy* 27: 550–563. https://doi.org/10.1016/j.landusepol.2009.07.009

Ahrens, A. and Lyons, S., 2019. Changes in land cover and urban sprawl in Ireland from a comparative perspective over 1990–2012. *Land* 8(1): 16.

Arneth, A., Denton, F., Agus, F., Elbehri, A., Erb, K., Osman Elasha, B., Rahimi, M., Rounsevell, M., Spence, A. and Valentini, R., 2019. Framing and context. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 77–129.

Baars, J.-R., 2011. Classical biological control for the management of alien invasive plants in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* 111B(3): 213–222.

Balcombe, P., Speirs, J.F., Brandon, N.P. and Hawkes, A., 2018. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts* 20: 1323–1339.

Black, K., O'Brien, P., Redmond, J., Barrett, F. and Twomey, M., 2009. The extent of peatland afforestation in Ireland. *Irish Forestry* 65: 61–71.

Bodnár, F., 2011. *Improving Food Security: A Systematic Review of the Impact of Interventions in Agricultural Production, Value Chains, Market Regulation, and Land Security*. IOB Study No. 363. Ministry of Foreign Affairs, The Hague, the Netherlands.

Bonsu, N.O., Dhubháin, Á.N. and O'Connor, D., 2019. Understanding forest resource conflicts in Ireland: a case study approach. *Land Use Policy* 80: 287–297. https://doi.org/10.1016/j.landusepol.2015.11.009

Bourdin, F., Sakrabani, R., Kibblewhite, M. and Lanigan, G., 2014. Effect of slurry dry matter content, application technique and timing on emissions of ammonia and greenhouse gas from cattle slurry applied to grassland soils in Ireland. *Agriculture, Ecosystems & Environment* 188: 122–133.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R. and Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B: Biological Sciences* 368(1621): 20130122.

Chapin III, F.S., Matson, P.A. and Vitousek, P., 2011. *Principles of Terrestrial Ecosystem Ecology*. Springer Science & Business Media, Berlin.

CHG (Department of Culture, Heritage and the Gaeltacht), 2019. *A Review of the Use of Peat in the Horticultural Industry*. Department of Culture, Heritage and the Gaeltacht, Dublin.

COFORD, 2017. *Growing the Irish Forest Bioeconomy*. Department of Agriculture, Food and the Marine, Dublin.

Creamer, R. and O'Sullivan, L., 2018. *The Soils of Ireland*. World Soils Book Series. Springer, Cham, Switzerland.

Creamer, R.E., Brennan, F., Fenton, O., Healy, M.G., Lalor, S.T., Lanigan, G., Regan, J. and Griffiths, B.S., 2010. Implications of the proposed Soil Framework Directive on agricultural systems in Atlantic Europe – A review. *Soil Use and Management* 26: 198–211.

CSO (Central Statistics Office), 2016. Milk statistics April 2016. CSO, Cork, Ireland. Available online: http://www.cso.ie/en/releasesandpublications/er/ms/milkstatisticsapril2016/ (accessed 26 February 2020).

CSO (Central Statistics Office), 2018. Environmental indicators Ireland: land use categories 1990–2016. CSO, Cork, Ireland. Available online: https://www.cso.ie/en/releasesandpublications/ep/*p*-eii/eii18/landuse/ (accessed 28 February 2020).

CSO (Central Statistics Office), 2019a. Quantity of agricultural output by statistic and year: 2019. CSO, Cork, Ireland. Available online: https://statbank.cso.ie/px/pxeirestat/Database/eirestat/Agricultural%20Output%20Input%20and%20Income/Agricultural%20Output%20Input%20and%20Income_statbank.asp?SP=Agricultural%20Output,%20Input%20and%20Income&Planguage (accessed 28 February 2020).

CSO (Central Statistics Office), 2019b. Value at current prices for output, input and income in agriculture by state, statistical indicator and year: 2019. CSO, Cork, Ireland. Available online: https://statbank.cso.ie/px/pxeirestat/Statire/SelectVarVal/Define.asp?maintable=AEA01&PLanguage=0 (accessed 15 June 2020).

CSO (Central Statistics Office), 2019c. Number of livestock in June by type of animal, region and year: 2019. CSO, Cork, Ireland. Available online: https://statbank.cso.ie/px/pxeirestat/Database/eirestat/Livestock/Livestock_statbank.asp?SP=Livestock&Planguage=0 (accessed 28 February 2020).

DAFM (Department of Agriculture, Food and the Marine), 2015a. *Food Wise 2025*. DAFM, Johnstown Castle, Ireland.

DAFM (Department of Agriculture, Food and the Marine), 2015b. *Forestry Programme 2014–2020: Ireland*. DAFM, Dublin.

DAFM (Department of Agriculture, Food and the Marine), 2016. *Report of the Pig Industry Stakeholder Group Ireland*. DAFM, Johnstown Castle, Ireland.

DAFM (Department of Agriculture, Food and the Marine), 2018. *Forest Statistics Ireland*. DAFM, Johnstown Castle, Ireland.

DAFM (Department of Agriculture, Food and the Marine), 2019. *Annual Review and Outlook for Agriculture, Food and the Marine*. DAFM, Johnstown Castle, Ireland.

DECC (Department of the Environment, Climate and Communications), 2020. National Waste Prevention Programme (NWPP): Food Waste. Available online: https://www.gov.ie/en/publication/19c9d-food-waste/ (accessed 27 July 2020).

Devaney, J.L., Redmond, J.J. and O'Halloran, J., 2015. Contemporary forest loss in Ireland; quantifying rare deforestation events in a fragmented forest landscape. *Applied Geography* 63: 346–356. https://doi.org/10.1016/j.apgeog.2015.07.008

Devaney, J., Redmond, J., Barrett, B., Cott, G. and O'Halloran, J., 2017. *21st Century Deforestation in Ireland*. EPA, Johnstown Castle, Ireland.

Dillon, E., Moran, B., Lennon, J. and Donnellan, T., 2019. *Teagasc National Farm Survey: 2018 Results. National Farm Survey*. Teagasc, Oakpark, Ireland.

Dillon, P., 2018. The evolution of grassland in the European Union in terms of utilisation, productivity, food security and the importance of adoption of technical innovations in increasing sustainability of pasture-based ruminant production systems. *Grassland Science in Europe* 23: 3–16.

Donnellan, T., Hennessy, T. and Thorne, F., 2015. *The End of the Quota Era: A History of the Dairy Sector and Its Future Prospects.* Teagasc, Athenry, Ireland.

EFFIS (European Forest Fire Information System), 2020. Annual Country Statistics for Ireland. European Commission. Available online: https://effis.jrc.ec.europa.eu/static/effis.statistics.portal/effis-estimates/EU/IE (accessed 9 September 2020).

EPA (Environmental Protection Agency), 2016. *Ireland's Environment 2016: An Assessment*. EPA, Johnstown Castle, Ireland.

EPA (Environmental Protection Agency), 2019. *Water Quality in Ireland 2013–2018*. EPA, Johnstown Castle, Ireland.

EPA (Environmental Protection Agency), 2020a. *Ireland's National Inventory Submissions 2020: Greenhouse Gas Emissions 1990–2018.* Reported to the United Nations Framework Convention on Climate Change. EPA, Johnstown Castle, Ireland.

EPA (Environmental Protection Agency), 2020b. *Ireland: Informative Inventory Report 2020: Air Pollutant Emissions in Ireland 1990–2018*. Reported to the Secretariat of the UNECE Convention on Long-Range Transboundary Air Pollution and to the European Union. EPA, Johnstown Castle, Ireland.

Eurostat, 2015. Main land use by land use type, EU-28. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics&oldid=389803 (accessed 6 March 2020).

Eurostat, 2018a. Thematic glossaries: agriculture, forestry and fisheries. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Thematic_glossaries (accessed 6 October 2020).

Eurostat, 2018b. Forestry: timber removals, wood products and trade. Available online: https://ec.europa.eu/eurostat/web/forestry/data/database (accessed 6 March 2020).

Eurostat, 2019. Environment: Greenhouse gas emissions by source sector. Available online: https://ec.europa.eu/eurostat/data/database (accessed 18 March 2020).

FAOSTAT, 2017. Food Balances (Old Methodology 1961 to 2013, New Methodology 2014 to 2017). Food and Agriculture Organization of the United Nations. Available online: http://www.fao.org/faostat/en/#data/FBSH (accessed 23 July 2020).

Farrelly, N. and Gallagher, G., 2015. The potential availability of land for afforestation in the Republic of Ireland. *Irish Forestry* 72: 120–138.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B. and Galloway, J.N., 2013. The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences* 368(1621): 20130164.

Fowler, D., Steadman, C.E., Stevenson, D., Coyle, M., Rees, R.M., Skiba, U., Sutton, M., Cape, J.N., Dore, A. and Vieno, M., 2015. Effects of global change during the 21st century on the nitrogen cycle. *Atmospheric Chemistry and Physics* 15: 13849–13893

Fridahl, M. and Lehtveer, M., 2018. Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. *Energy Research & Social Science* 42: 155–165. https://doi.org/10.1016/j.erss.2018.03.019

Friedlingstein, P., Jones, M.W., O'Sullivan, M., *et al*., 2019. Global carbon budget 2019. *Earth System Science Data* 114: 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

FSAI (Food Safety Authority of Ireland), 2017. *Healthy Eating, Food Safety and Food Legislation: A Guide Supporting the Healthy Ireland Food Pyramid*. FSAI, Dublin.

Grace, C., Boland, T.M., Sheridan, H., Lott, S., Brennan, E., Fritch, R. and Lynch, M.B., 2018.The effect of increasing pasture species on herbage production, chemical composition and utilisation under intensive sheep grazing. *Grass and Forage Science* 73: 852–864.

Grace, C., Lynch M., Sheridan, H., Lott, S., Fritch, R. and Boland, T., 2019. Grazing multispecies swards improves ewe and lamb performance. *Animal* 13: 1721–1729.

Haughey, E., Suter, M., Hofer, D., Hoekstra, N.J., McElwain, J.C., Lüscher, A. and Finn, J.A., 2018. Higher species richness enhances yield stability in intensively managed grasslands with experimental disturbance. *Scientific Reports* 8(1): 15047. https://doi.org/10.1038/s41598-018-33262-9

Haughey, E., Benton, T., Cowie, A., Olsson, L. and Smith, P., 2019. Cross-Chapter Box 6 – Agricultural intensification: land sparing, land sharing and sustainability. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 502–505.

Hofer, D., Suter, M., Haughey, E., Finn, J.A., Hoekstra, N.J., Buchmann, N. and Lüscher, A., 2016. Yield of temperate forage grassland species is either largely resistant or resilient to experimental summer drought. *Journal of Applied Ecology* 53: 1023–1034. https://doi.org/10.1111/1365-2664.12694

Hurlbert, M., Krishnaswamy, J., Davin, E., *et al*., 2019. Risk management and decision making in relation to sustainable development. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 673–800.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), 2019. Summary for policymakers. In Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., *et al.* (eds), *Global Assessment Report On Biodiversity and Ecosystem Services*. IPBES, Bonn, Germany, p. 56. https://doi.org/10.5281/zenodo.3553579

IPCC (International Panel on Climate Change), 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Eggleston, H.S., Buendia, I., Miwa, K., Ngara, T. and Tanabe, K. (eds). Published by the Institute for Global Environmental Strategies (IGES), Japan.

IPCC (International Panel on Climate Change), 2010. *Revisiting the Use of Managed Land as a Proxy for Estimating National Anthropogenic Emissions and Removals*. Meeting Report, 5–7 May 2009, INPE, São José dos Campos, Brazil. Published by the Institute for Global Environmental Strategies (IGES), Japan.

IPCC (International Panel on Climate Change), 2018. Summary for policymakers. In Masson-Delmotte, V., Zhai, P., Pörtner, H.-O. *et al*. (eds), *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. World Meteorological Organization, Geneva, Switzerland, p. 32.

IPCC (International Panel on Climate Change), 2019a. Summary for policymakers. In Shukla, P.R., Skea, J., Calvo, Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, p. 41.

IPCC (International Panel on Climate Change), 2019b. Annex I: Glossary. van Diemen, R. (ed.). In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 803–829.

Jia, G., Shevliakova, E., Artaxo, P., *et al*., 2019. Land–climate interactions. In Shukla, P.R., Skea, J., Calvo, Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 131–247.

Kavanagh, I., Burchill, W., Healy, M.G., Fenton, O., Krol, D.J. and Lanigan, G.J., 2019. Mitigation of ammonia and greenhouse gas emissions from stored cattle slurry using acidifiers and chemical amendments. *Journal of Cleaner Production* 237:117822. https://doi.org/10.1016/j.jclepro.2019.117822

Lanigan, G., Donnellan, T., Hanrahan, K., *et al*., 2018. *An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021–2030*. Teagasc, Carlow, Ireland.

Long, M., Jennings, P. and Carroll, R., 2011. Irish peat slides 2006–2010. *Landslides* 8: 391–401.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M. and Peyraud, J.L., 2014. Potential of legume-based grassland–livestock systems in Europe: a review. *Grass and Forage Science* 69: 206–228. https://doi.org/10.1111/gfs.12124

McAdam, J., 2018. Adoption of agroforestry options in land use policy measures in northern and southern Ireland. Presented at Fourth European Agroforestry Conference: Agroforestry as Sustainable Land Use, Nijmegen, the Netherlands, 28–30 May 2018.

McDaniel, M.D., Saha, D., Dumont, M.G., Hernández, M. and Adams, M.A., 2019. The effect of land-use change on soil CH_4 and N_2O fluxes: a global meta-analysis. *Ecosystems* 22: 1424–1443. https://doi.org/10.1007/s10021-019-00347-z

McGeever, A.H., Price, P., McMullin, B. and Jones, M.B., 2019. Assessing the terrestrial capacity for negative emission technologies in Ireland. *Carbon Management* 10(1): 1–10. https://doi.org/10.1080/17583004.2018.1537516

Martínez-Botí, M.A., Foster, G.L., Chalk, T.B., Rohling, E.J., Sexton, P.F., Lunt, D.J., Pancost, R.D., Badger, M.P.S. and Schmidt, D.N., 2015. Plio-Pleistocene climate sensitivity evaluated using high-resolution CO_2 records. *Nature* 518(7537): 49–54. https://doi.org/10.1038/nature14145

Matthews, R., Mortimer, N., Lesschen, J.P., Lindroos, T.J., Sokka, L., Morris, A., Henshall, P., Hatto, C., Mwabonje, O. and Rix, J., 2015. *Carbon Impacts of Biomass Consumed in the EU: Quantitative Assessment*. Final project report, project DG ENER C 1. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/EU%20Carbon%20Impacts%20of%20Biomass%20Consumed%20in%20the%20EU%20final.pdf (accessed 2 March 2021).

Mbow, C., Smith, P., Skole, D., Duguma, L. and Bustamante, M., 2014. Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability* 6: 8–14.

Mbow, C., Rosenzweig, C., Barioni, L.G., *et al*., 2019. Food security. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 437–550.

Meehan, P., Burke, B., Doyle, D., Barth, S. and Finnan, J., 2017. Exploring the potential of grass feedstock from marginal land in Ireland: does marginal mean lower yield? *Biomass and Bioenergy* 107: 361–369.

Meredith, D., Heanue, K., Rannou, M. and O'Gorman, C., 2015. *Attitudes to Farm Diversification*. Teagasc Technology Update. Teagasc Rural Economy and Development, Oak Park, Ireland.

Mitchell, F., 2000. The development of Ireland's tree cover over the millennia. *Irish Forestry* 56: 39–57.

Moroney, A., O'Reilly, S. and O'Shaughnessy, M., 2016. Taking the leap and sustaining the journey: diversification on the Irish family farm. *Journal of Agriculture, Food Systems, and Community Development* 6: https://doi.org/10.5304/jafscd.2016.064.004

Mullan, D., 2013. Soil erosion under the impacts of future climate change: assessing the statistical significance of future changes and the potential on-site and off-site problems. *CATENA* 109: 234–246. https://doi.org/10.1016/j.catena.2013.03.007

Murphy, J.D. and Power, N.M., 2009. An argument for using biomethane generated from grass as a biofuel in Ireland. *Biomass and Bioenergy* 33: 504–512. https://doi.org/10.1016/j.biombioe.2008.08.018

Myhre, G., Shindell, D., Bréon, F.-M., *et al*., 2013. Anthropogenic and natural radiative forcing. In Stocker, T.F., Qin, D., Plattner, G.-K. *et al*. (eds), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

NPWS (National Parks and Wildlife Service), 2019. *The Status of EU Protected Habitats and Species in Ireland*. Volume 1: Summary Overview. Unpublished NPWS report. NWPS, Dublin, Ireland.

O'Donovan, M., Hennessy, D. and Creighton, P., 2018. Ruminant grassland production systems in Ireland. *Grassland Science in Europe* 23:17–25.

Olsson, L., Barbosa, H., Bhadwal, S., *et al*., 2019. Land degradation. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 345–436.

O'Mara, F.P., 2008. *Country Pasture/Forage Resource Profile: Ireland*. FAO, Rome, Italy. Available online: http://www.fao.org/AG/agp/agpc/doc/Counprof/PDF%20files/Ireland.pdf (accessed 29 May 2020).

Pan, B., Lam, S.K., Mosier, A., Luo, Y. and Chen, D., 2016. Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. *Agriculture, Ecosystems & Environment* 232: 283–289. https://doi.org/10.1016/j.agee.2016.08.019

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L. and Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy* 54: 438–447.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the USA* 109(31): 12302–12308. https://doi.org/10.1073/pnas.0912953109

Posthumus, H., Morris, J., Hess, T.M., Neville, D., Phillips, E. and Baylis, A., 2009. Impacts of the summer 2007 floods on agriculture in England. *Journal of Flood Risk Management* 2: 182–189. https://doi.org/10.1111/j.1753-318X.2009.01031.x

Pretty, J., Benton, T.G., Bharucha, Z.P., *et al*., 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability* 1: 441–446. https://doi.org/10.1038/s41893-018-0114-0

Renou-Wilson, F., 2018. Peatlands. In Creamer, R. and O'Sullivan, L. (eds), *The Soils of Ireland*. World Soils Book Series. Springer International Publishing, Cham, Switzerland. https://doi.org/10.1111/gcb.13325

Renou-Wilson, F., Müller, C., Moser, G. and Wilson, D., 2016. To graze or not to graze? Four years greenhouse gas balances and vegetation composition from a drained and a rewetted organic soil under grassland. *Agriculture, Ecosystems & Environment* 222: 156–170.

Saunois, M., Stavert, A.R., Poulter, B., *et al*., 2019. The global methane budget 2000–2017. *Earth System Science Data* 2019: 1–136. https://doi.org/10.5194/essd-12-1561-2020

Secondi, L., Principato, L. and Laureti, T., 2015. Household food waste behaviour in EU-27 countries: a multilevel analysis. *Food Policy* 56: 25–40. https://doi.org/10.1016/j.foodpol.2015.07.007

Sheehy-Skeffington, M.J. and Curtis, T.G.F., 1998. The salt marshes of Ireland: an inventory and account of their geographical variation. *Biology and Environment: Proceedings of the Royal Irish Academy* 98B(2): 87–104.

Sirin, A., Suvorov, G., Chistotin, M. and Glagolev, M., 2012. Values of methane emission from drainage ditches. *Environmental Dynamics and Global Climate Change* 3(2): 1–10.

Smith, P., Nkem, J., Calvin, K., *et al*., 2019. Interlinkages between desertification, land degradation, food security and greenhouse gas fluxes: synergies, trade-offs and integrated response options. In Shukla, P.R., Skea, J., Calvo Buendia, E. *et al*. (eds), *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. World Meteorological Organization, Geneva, Switzerland, pp. 551–672.

Teagasc, 2018a. *Energy Efficiency on Poultry Farms. Energy in Agriculture 2018*. Teagasc, Carlow, Ireland.

Teagasc, 2018b. *Energy Use On Pig Farms. Energy in Agriculture 2018*. Teagasc, Carlow, Ireland.

Teagasc, 2020. Agroforestry: combining trees with grazing or silage. Teagasc. Available online: https://www.teagasc.ie/crops/forestry/grants/establishment-grants/agroforestry/ (accessed 19 August 2020).

Thorne, P., Keane, A., Hitzman, M., *et al*., 2020. *Leveraging Ireland's R&D for Successfully Tackling the Climate and Biodiversity Emergency*. The All-Island Climate and Biodiversity Research Network. Available online: https://www.icrag-centre.org/t4media/All-Island-Climate-and-Biodiversity-Research-Network-Final.pdf (accessed 2 March 2021).

Tiernan, D., 2008. Redesigning afforested western peatlands in Ireland. In *After Wise Use – The Future of Peatlands*, Proceedings of the 13th International Peat Congress. Peatland Forestry, Tullamore, Ireland, pp. 8–13.

Vladimir, Č. and Nataša, M.P., 2014. Crop insurance – risks and models of insurance. *Economics of Agriculture* 61(297–2016–3608): 561–573.

Wall, D. and Dillon, E., 2017. Fertiliser use in Ireland 2005–2015. Teagasc National Farm Survey. Paper presented at the Fertiliser Association of Ireland Workshop, Kildalton College, Co. Kilkenny, Ireland, 4 May 2017.

Walsh, A., Sullivan, C., Waldren, S. and Finn, J.A., 2019. Development of a scoring method to identify important areas of plant diversity in Ireland. *Journal for Nature Conservation* 47: 1–11.

Wilson, D., Müller, C. and Renou-Wilson, F., 2013. Carbon emissions and removals from Irish peatlands: present trends and future mitigation measures. *Irish Geography* 46(1–2): 1–23.

Wilson, D., Farrell C.A., Fallon, D., Moser, G., Müller, C. and Renou-Wilson, F., 2016. Multiyear greenhouse gas balances at a rewetted temperate peatland. *Global Change Biology* 22(12): 4080–4095.

WMO (World Meteorological Organization), 2019. *WMO Greenhouse Gas Bulletin No. 15: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018*. WMO, Geneva, Switzerland.

Xu, W., Yiotis, C., Kamber, B.S., Gill, L.W. and McElwain, J.C., 2019. Exploration and optimisation of a novel negative carbon emission technology using enhanced plant-mediated chemical weathering. Paper presented at the New Phytologist Next Generation Scientists, Dublin, Ireland, 22–25 July 2019.

Zimmermann, J., González, A., Jones, M.B., O'Brien, P., Stout, J.C. and Green, S., 2016. Assessing land-use history for reporting on cropland dynamics – A comparison between the Land-Parcel Identification System and traditional inter-annual approaches. *Land Use Policy* 52: 30–40. https://doi.org/10.1016/j.landusepol.2015.11.027

Abbreviations

AFOLU	Agriculture forestry and other land use
BECCS	Bioenergy with carbon capture and storage
CAP	Common Agricultural Policy (of the EU)
CCS	Carbon capture and storage
EU-28	The first 28 Member States of the EU (1 July 2013 to 31 January 2020)
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land use change and forestry
MACC	Marginal abatement cost curve
NFI	National Forest Inventory (Ireland)
RCP	Representative Concentration Pathway
SRCCL	IPCC Special Report on Climate Change and Land (2019)
SSP	Shared Socioeconomic Pathways

Appendix 1 Integrated Response Options

The assessment of potential applicability of integrated response options to Ireland and associated caveats are reported in detail in Table A1.1. The potential applicability of each option is rated low (L), moderate (M) or high (H) according to a range of general criteria. Note that, for many options, specific criteria further to those outlined above were required to assess applicability.

Table A1.1. Assessment of the applicability to Ireland of integrated response options assessed in the SRCCL

SRCCL response option	Potential applicability – justification/notes	Rating
Demand management		
Dietary change	High potential: this option is potentially applicable to the general population in Ireland. This encompasses multiple major sectors of the food system (from production, retail and restaurants, and consumers) Further justification: the transition to "sustainable healthy" diets is highly relevant to Ireland owing to the high overall available food supply and level of animal protein consumption (FAOSTAT, 2017) There are significant barriers to transitioning to sustainable healthy diets and there is *low confidence* regarding the impact of this response option on climate mitigation and adaptation in Ireland	H
Reduced post-harvest losses	Low potential: this option is likely to be "effectively" deployed already, with only minimal levels of food loss occurring at this stage of the value chain in Ireland Further justification: currently a relatively high level of technology is deployed in the production of food in Ireland There may be sector-specific exceptions to this assessment, in which case improvement may be possible	L
Reduced food waste (consumer or retailer)	High potential: this option is potentially applicable to multiple major components (sectors) of the food system (consumers and retail) Further justification: food loss and waste at the consumer stage is a significant problem in Ireland (DECC, 2020) In 2015, Ireland was assessed as one of the most food-wasting nations in the EU, based on the percentage of population who waste more than 5% of food purchased (Secondi *et al.*, 2015). Therefore, there is high potential to deploy this response option	H
Material substitution	Moderate potential: applies mainly to the construction sector. As noted in section 3.3.1, the use of harvested wood products, which play a role in carbon sequestration, has significant potential in Ireland. There is also potential to use natural materials from the agriculture sector as alternative insulation material in buildings (such as wool, straw or other cellulosic crop by-products) Further justification: in Europe there is currently relatively high reliance on building materials such as concrete and steel. Therefore, there is significant potential to transition to the use of timber products in building construction	M

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Supply management		
Sustainable sourcing	Moderate potential: this option partly applicable (directly) to several sectors (retail and agriculture and forestry) in Ireland (*low confidence*) Further justification: this option is particularly important for imported commodity crops/products and, therefore, has limited impact (directly) on the land system in Ireland. However, certification options do apply directly to food produced in Ireland and forestry products (e.g. Forest Stewardship Council accreditation) However, the option does apply to the agriculture system (in part) through value-added food labelling that supports sustainability of food production (e.g. Origin Green)	M
Management of supply chains	Low potential: this option is applicable to several sectors in Ireland, primarily the retail sector, but is most likely near the point of limited returns in terms of technology deployment (*low confidence*) Further justification: this option has limited applicability across multiple sectors of the food system and it is likely that it is already being deployed at a relatively high level of efficiency There is a lack of direct data about the likely effectiveness of interventions in Ireland, indicating a knowledge gap	L
Enhanced urban food systems	Low potential: this option currently applies to only a small portion of the horticulture sector in Ireland, primarily to high-value salad crops (*low confidence*) Further justification: Ireland has a relatively low population density in urban areas, making this option less relevant This option could become more important in the future as a result of the impact of climate change on food prices and availability, but there is no evidence at present to suggest that this is likely to occur in Ireland	L
Improved food processing and retailing	Low potential: this option is applicable to the food processing and retail sectors and meets the general criteria for moderate potential, but it is likely to be near saturation point, with limited returns on further improvements (*low confidence*) Further justification: the largest gains are to be made in developing economies where there has been low technological development in the food sector to date	L
Improved energy use in food systems	Moderate potential: this option applies to several main subsectors of agriculture (pig, poultry and dairy) but “effective” deployment of efficient technologies is most likely already at a relatively high level Further justification: owing to the intensification of production in these sectors, energy efficiency at individual farm level has a higher impact and represents a moderate mitigation opportunity Research by Teagasc (2018a,b) indicates that there is considerable scope to improve energy use efficiency on pig and poultry farms	M
Risk management		
Management of urban sprawl	Moderate potential: infrastructure accounts for a moderate area of land cover in Ireland [at 2.47% according to CORINE (2018)]. Between 1990 and 2012 Ireland experienced a higher rate of conversion to infrastructure than the EU average (Ahrens and Lyons, 2019). Although urban sprawl applies only to a small subset of the total infrastructure area, this is an issue of increasing concern Further justification: cropland could be at risk because of the overlap between cropland area and the densest infrastructure cover in the east and south-east	M
Livelihood diversification	Moderate potential: this option applies (in part) to many rural communities and farms in the agriculture and forestry sectors in Ireland, especially those reliant on a small number of commodity products (such as beef production) Further justification: diversification can have socioeconomic benefits through increased resilience due to income stream diversification. This option is less likely to be applicable to farming sectors that are currently highly profitable	M

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Use of local seeds	Low potential: this option is not applicable (or only partly applicable) to food production in Ireland Further justification: this option could apply to the horticulture sector at a small scale. However, the use of local seeds needs to be weighed against the use of higher-performance cultivars that are commercially available	L
Disaster risk management	Moderate potential: this option applies to at least a moderate area of natural and managed land (agricultural land, forests, seminatural areas, peatland) at risk of climate-related events such as flooding, drought, wildfire, landslides and mudslides (*low confidence*) Further justification: it is likely that the applicability of this response option will further increase in the future as a result of climate change impacts on the land system. This report has not assessed in detail the risk posed by climate change to human and natural systems in Ireland and, therefore, there is relatively *low confidence* in this assessment	M
Risk-sharing instruments	Moderate potential: currently this type of option (in terms of crop insurance) is probably applicable to only a small portion of the crop/horticulture sectors. However, it is likely that climate change will make crop insurance (or other agricultural insurance) more important Further justification: typically crop insurance in western Europe (and Ireland) is available only for crop damage caused by a limited number of specific factors, such as hail (Vladimir and Nataša, 2014)	M
Agriculture land management		
Increased food productivity	High potential: this option is applicable across all sectors of agricultural production Further justification: this approach comes with significant caveats in the form of potential negative impacts due to rebound effects. Note that this suite of options is not confined to increasing the intensity of land management This option can be considered an umbrella term, as it overlaps considerably with other response options, and is system and location specific, making it difficult to specify to which agricultural sectors it is most applicable	H
Improved cropland management	Moderate potential: this option applies to a moderate area (CORINE, 2018) and a single major agriculture sector Further justification: this suite of actions could apply across a moderate land area (cropland accounts for 4.64% of total land cover; CORINE, 2018) and across the main cereal crops in Ireland. However, in the case of many options it is likely that current practices are already at an advanced level or near the point of diminishing returns (e.g. soil carbon levels are already high)	M
Improved grazing land management	High potential: this option applies to a large area of land cover (CORINE, 2018) and several major agriculture sectors Further justification: grassland cover and the associated ruminant livestock sectors (beef, dairy and sheep) are dominant in Ireland. Major national research programmes, examining more efficient grazing management, including the increased use of multispecies grassland swards and improved grass and clover cultivars, are currently under way A relatively high risk of rebound effects is associated with application of this option	H
Improved livestock management	High potential: this option applies across several major agriculture sectors (livestock based) Further justification: this option applies to the grazing and non-grazing livestock sectors. Considerable national research programmes to improve the efficiency of livestock production are currently under way. This includes a focus on reduction in GHG emissions per unit of product produced A relatively high risk of rebound effects is associated with this option	H

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Agroforestry	High potential: this option could apply to a large area of grassland or cropland and across multiple sectors of the food production system Further justification: although the potential scale of deployment is large, it is difficult to assess what level is feasible (owing to competition with other land uses). This option could be applied in conjunction with livelihood and agriculture diversification measures Uptake of agroforestry systems in Ireland is currently very low, indicating strong barriers (socioeconomic and institutional)	H
Agricultural diversification	High potential: this option could apply across agricultural sectors and to a large potential land area. Further justification: as noted in Chapter 2, the agriculture sector in Ireland is dominated by the production of a relatively small number of commodity products such as beef, dairy products and cereals. There is, therefore, considerable scope to diversify This is an umbrella option encompassing several others (including soil management and forestry)	H
Reduced grassland conversion to cropland	Low potential: the land area likely to be converted to cropland in Ireland is negligible. However, where this does apply it could have significant benefits in reducing the loss of soil carbon Further justification: there could be loss of opportunity costs associated with limiting conversion of grassland to arable land This option could limit the increase in agricultural diversification where more horticultural products are produced	L
Integrated water management	Moderate potential: this option currently has low applicability to Ireland but its applicability is likely to increase in the future as a result of climate change pressures (*low confidence*) Further justification: irrigation does not apply to a major land area or main sector (horticulture) but may become more important in the future as a result of climate change In the context of this report, this option is focused on water use for irrigation of agricultural land (see Table 4.1). Water management in relation to water quality and biodiversity is not included but would have very high significance for Ireland	M
Soil-based land management		
Increased soil organic carbon content	Moderate potential: this option could apply to soils over a large area (> 5% land cover) but is most likely close to saturation in many soils Further justification: specifically, this option could apply to all mineral soils under agricultural management; however, the organic matter content of soils in Ireland is generally already accepted to be high and, therefore, the capacity of these soils to continue as major carbon sinks is likely to be limited in the coming decades Uncertainty regarding the mitigation potential associated with this option in Ireland is high. A better understanding of how land management interacts with soil carbon sequestration across multiple soil types is required	M
Reduced soil erosion	Low potential: this option applies to a small area of land in Ireland, and most specifically to the arable land area. It is uncertain if erosion will be exacerbated by climate change (*low confidence*) Further justification: estimated rates of soil erosion in Ireland are well below the EU-28 average (Panagos *et al*., 2015) and within the range that is regarded as “acceptable” (Mullan, 2013). A high level of variability between sites should be expected and a national measured dataset is lacking This issue could become more important in the future as rainfall patterns become more extreme. Further investigation of the risks of more extreme rainfall patterns is required to assess their likelihood	L

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Reduced soil salinisation	Low potential: this option applies to a small land area in Ireland (*low confidence*) Further justification: salinisation is not a major issue in temperate maritime regions such as Ireland. However, it can be a side-effect of the increased use of irrigation, which is likely to expand in the future There are no known national studies investigating this issue in Ireland and, therefore, confidence in this assessment is limited	L
Reduced soil compaction	Moderate potential: this option applies to intensively managed grassland and cropland in Ireland. The extent of soil compaction in Ireland is not clear, but the risk is likely to increase with climate change Further justification: compaction of soil has been identified as a risk to soil health and the productivity of both arable- and grassland-based livestock agriculture in Ireland (as part of the Atlantic Europe region) (Creamer *et al*., 2010) Soil compaction is often linked to soil moisture conditions, which affect trafficability (Posthumus *et al*., 2009). Therefore, increased variation in rainfall patterns in the future is likely to interact in a negative manner with soil compaction	M
Biochar addition to soil	Moderate potential: biochar could be applied to a moderate to large area, comprising cropland and, possibly, grassland (McGeever *et al*., 2019) Further justification: significant barriers to deployment include sourcing feedstock, production scale-up and the cost of application by farmers There is significant uncertainty regarding the area to which biochar could be applied sustainably	M
Soil/land management for CO_2 removal		
Enhanced weathering of minerals	Low potential: it is not known if this option could be applied at scale in Ireland Further justification: at present this option is at experimental level in terms of scale, and likely to be so in the short to medium term This option could potentially be applied to a wide range of soil types in Ireland, and work is under way to investigate its potential in grassland systems (Xu *et al*., 2019). However, major knowledge gaps exist regarding the feasibility of implementation at scale (McGeever *et al*., 2019) Considerable further research and development is required	L
Bioenergy and BECCS	High potential: this option could be applied to a large area of land (cropland and grassland). There is a high degree of uncertainty regarding the feasible scale of deployment, depending on the type of bioenergy crop or biomass source used Further justification: the potential applicability of this option to cropland is limited owing to demands for food and feed production from a limited area suitable for crops. There could be considerable scope to increase the area if this option were to be applied to marginal grassland (in the case of willow biomass). In the context of this report CCS technologies are not within scope	H
Forest land management		
Forest management	Moderate potential: this option could apply to a significant proportion of the forested land in Ireland (likely to be a moderate proportion of total land cover) Further justification: forest land in Ireland is dominated by monoculture cultivation of non-native conifer species. Therefore, it is likely that there is considerable scope to implement sustainable forest management practices that strike a balance between biomass production and other services such as carbon sequestration in soils, biodiversity and water quality/flood management	M

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Reduced deforestation and forest degradation	Low potential: this option is likely to apply to only a very small area of forested land in Ireland (Devaney *et al.*, 2015) Further justification: deforestation affects a small proportion of overall forest area in Ireland. Most natural forest is already protected and, therefore, there is limited scope for forest degradation. Note that forest degradation could be exacerbated by climate change (e.g. by a higher risk of natural disasters such as wildfires and landslides)	L
Reforestation and forest restoration	Low potential: this option is likely to apply to only a very small area of land in Ireland Further justification: "historically forested" land is interpreted here to refer to land that was under forest in the last 100–150 years. Ireland had very low levels of forest cover in 1990. Once much of Ireland was forested, but the forested area has seen a steady decline over the last several thousand years (Mitchell, 2000)	L
Afforestation	High potential: this option could be applied to a large area of land (most likely with co-benefits for food security where applied to grassland as opposed to cropland) Further justification: there is significant scope to increase the area of forestry in Ireland, where the level of forest cover is relatively low compared with the EU average The level of afforestation that is achievable will be limited in practice by competition for land for other uses, primarily agriculture but also conservation	H
Other ecosystems land management		
Fire management	Moderate potential: this option currently applies to a relatively small area: between 2010 and 2019 an average of 4605 ha $year^{-1}$ was burnt (EFFIS, 2020). However, based on global trends, this is likely to be amplified by climate change (*low confidence*) Further justification: a detailed assessment of climate change impacts on fire regimes for natural and managed ecosystems in Ireland is required to quantify the associated risk	M
Reduced landslides and natural hazards	Moderate potential: this option is likely to apply to a only small area (currently), but climate change is likely to increase the area to which this option could apply (*low confidence*) Further justification: it is expected that more variable rainfall regimes will increase the likelihood of landsides, but with limited global evidence (Olsson *et al.*, 2019). In Ireland, peatlands are particularly susceptible to landslide/mudslides when extreme rainfall events occur (Long *et al.*, 2011) Regarding this assessment, systematic information collected on the occurrence of landslides, mudslides and rockfalls in Ireland is lacking. There is also much uncertainty regarding the potential for future amplification by climate change	M
Reduced pollution including acidification	High potential: this option applies to a large land area and across multiple agriculture sectors Further justification: this option is particularly important for intensively managed agriculture, as excess application and volatilisation of nutrients can result in pollution. For example, ammonia emissions are a significant air pollution issue and are associated with excessive nutrient addition to agricultural land Eutrophication of waterways due to leaching and run-off of nutrients is primarily driven by agriculture in Ireland (EPA, 2019)	H
Management of invasive species/encroachment	Low potential: this option currently applies to a relatively small area (*low confidence*) Further justification: levels of "environmental weeds" and invasive species in Ireland are generally low (Baars, 2011) An analysis which synthesises across disciplines was not found. This is a significant knowledge gap. Climate change could exacerbate the dominance of some invasive species and lead to greater levels of encroachment, but large uncertainties exist	L

Table A1.1. Continued

SRCCL response option	Potential applicability – justification/notes	Rating
Restoration and reduced conversion of coastal wetlands	Low potential: evidence suggests that the extent of currently degraded coastal wetlands is minimal (<1% of total land area) Further justification: this type of land cover was not part of the assessment conducted in this report. Therefore, there is relatively *low confidence* associated with this assessment In terms of their biodiversity and function, salt marshes in Ireland are rare, and their conservation is, therefore, particularly important (Sheehy-Skeffington and Curtis, 1998)	L
Restoration and reduced conversion of peatlands	High potential: this option applies to a single large land class – peatlands (>5% of total land area; CORINE, 2018) Further justification: there is considerable scope to reduce current degradation of peatlands in Ireland and to implement restoration of peatlands that are already degraded (Wilson *et al*., 2016) In some cases, it may not be feasible to restore peatlands, but it may still be possible to reduce GHG emissions from them through appropriate interventions	H
Biodiversity conservation	High potential: this option applies across managed and unmanaged land in Ireland Further justification: conservation of biodiversity potentially applies across large areas and different types of land cover and use. Many areas of concern are already protected, but threatened species occur outside these areas (Walsh *et al*., 2019)	H

Potential applicability is based on a combined assessment of current and future relevance to the land system (including the food system) and the area of land or economic importance of the sector to which the option applies. For each option, justification and notes are provided. Potential applicability is rated low (L), moderate (M) or high (H). Where confidence in the assessment is low, due to limited data, limited literature or was beyond the main scope of this report, it has been indicated.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- 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 cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 371

Climate Change and Land Use in Ireland

Author: Eamon Haughey

Identifying Pressures

Land supports a broad range of ecosystem services, including biodiversity and carbon storage, as well as economic outputs in the agriculture and forestry sectors. This project identified pressures in the land system in Ireland by analysing land use and outputs as well as greenhouse gas emissions associated with the land system. Ireland faces a specific set of challenges in terms of greenhouse gas emissions related to the land system. The dominance of grasslands and ruminant livestock-based agriculture means that a relatively large proportion of Ireland's total greenhouse gas emissions are attributable to the agriculture sector. Furthermore, relatively low forest cover, declining rates of afforestation and a large area of degraded peatlands means that the land use, land use change and forestry sector in Ireland is also a significant net source of greenhouse gas emissions.

Informing Policy

The high-level overview of Ireland's land use system and its outputs carried out for this report considered key messages from the Intergovernmental Panel on Climate Change Special Report on Climate Change and Land in a national context and found that agriculture and the land use change and forestry sectors clearly present major challenges to the achievement of Ireland's climate mitigation goals. The IPCC report describes 40 integrated response options to adapt to climate change and mitigate its effects. An analysis of the extent to which these integrated response options are applicable to Ireland found that 12 of the 40 were highly applicable. The analysis also identified areas where there are significant knowledge gaps and where further research is needed to enable increased uptake of response options. The analysis of response options, although at a high level, can be used to inform policy in Ireland with the aim of improving the impact of climate mitigation and adaption actions and identifying potential synergies.

Developing Solutions

A range of highly applicable options are available to simultaneously address climate change mitigation and adaptation in the land system in Ireland. Of note is that several of the options applicable to the agriculture sector are aimed at increasing productivity, but, if not carefully implemented, these could in fact increase overall greenhouse gas emissions as a result of rebound effects. Other options, such as agroforestry and agricultural diversification, face major barriers to uptake and this report recommends research that should be carried out to better inform policymakers. However, in many cases it is difficult to estimate the potential impact of response options because local data and analysis are limited. The report also identifies knowledge gaps in relation to national land use mapping, which currently limit the potential for regional analyses of land–climate interactions. Nevertheless, this report provides the basis for prioritising future research at the land–climate interface. Such work can also contribute to international efforts to develop scalable land-based solutions to climate change.

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

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

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/