Working Paper

Climate Change Mitigation and the Irish Agriculture and Land Use Sector

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Disclaimer

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Executive Summary

In its Annual Review 2018, the Climate Change Advisory Council (CCAC) stated that Ireland is not on a trajectory to meet greenhouse emission reduction targets. The Agriculture sector, the predominant land use in Ireland, is a major and increasing source of greenhouse gasses, currently accounting for 33% of Ireland's national greenhouse emissions. Land use also currently represents a net source of emissions. The potential for greenhouse gas mitigation within agriculture, forestry and other land use (AFOLU) is well recognised and achievable through the collective implementation of multiple mitigation measures.

This expert working paper was commissioned by the Climate Change Advisory Council secretariat in response to the council's request for further information following a seminar on agriculture and forestry, hosted by the Climate Change Advisory Council in September 2018. The purpose of this document is to provide the council with science-based discussion on options regarding greenhouse gas mitigation within the AFOLU sector. More specifically, this paper aims to inform the council on (i) the Irish AFOLU sector (ii) the associated greenhouse gas emissions profile (iii) potential greenhouse gas mitigation options and (iv) related issues that may require policy development to enable transition within the sector.

The paper consists of a detailed literature review and analysis of a number of indicative scenarios for the sector. In addition, the authors conducted a series of semi-structured interviews with selected experts, between November 2018 and April 2019. Public and stakeholder acceptability of the mitigation options presented in the working paper have not been considered in detail. It is emphasised that mitigation options outlined would require consultation and engagement with relevant stakeholders prior to potential implementation.

The paper finds that (i) there is an urgent need for changes in management within the AFOLU sector while (ii) the necessity for change also presents opportunity, to tackle climate change, but also to provide multiple co-benefits to society.

In addition to greenhouse gas emissions, agricultural activity appears in certain cases, to be causing environmental degradation, while also generating insufficient economic returns. In its current structure, the sustainability of the Irish agricultural sector is at risk. Farmers, as key land managers, have successfully responded to policy, market and institutional signals in the past, and will form a necessary part of the solution. Their knowledge and expertise should be recognised as crucial in addressing challenges.

Agriculture is at the core of rural communities and identity across Ireland and has societal value beyond just the production of food. Change will be challenging, but the benefits to those involved and wider society, will be substantial if appropriately implemented. Regarding other land use, current low afforestation rates are considerably below target, which may limit the contribution that forestry can make to future greenhouse gas mitigation, while the continued drainage of peatlands and organic soils is a significant source of carbon dioxide emissions.

The following mitigation options to should be considered:

1. A gradual reduction in national bovine numbers may be necessary to achieve greenhouse gas emission reduction. This may also help address localised environmental degradation if implemented appropriately. Further expansion of the dairy herd may increase the risk of additional adverse environmental impacts. Continuation of the observed decline in suckler cow numbers, in conjunction with stabilisation of dairy cow numbers, would represent an important contribution to national efforts to reach Effort Sharing Regulation targets. Any reductions in animal numbers should be facilitated by long-term and consistent supports for stable incomes to provide favourable environmental outcomes through land management.
2. Management options for wetlands, especially peatland, require urgent assessment and implementation. Time is of the essence, as it will take a number of years for peatland ecosystems to re-establish and built resilience to projected changes in climate. The drainage of peat for multiple land uses, including peat extraction, must cease. Areas for rewetting should be identified and associated land management programmes started. Identification of agricultural land on which drainage has already ceased is required for inventory

accounting. Bord na Móna's plans for peatlands under its management are an important opportunity for leadership, learning and public engagement.

3. Low afforestation rates need to be addressed with recognition and consideration of behavioural barriers. The type of afforestation, in terms species and environmental impacts, needs to be considered. Agroforestry appears to be a resilient system that permits agricultural production with limited afforestation, bringing multiple co-benefits and with further research, should be encouraged.
4. Expanding on approaches in the National Planning Framework, there is merit in the development of a national land use strategy. This should not be prescriptive but would enable design of policy to promote the sustainable delivery of multiple and competing land functions, while ensuring long-term environmental sustainability.
5. Cost-effective mitigation measures, identified in the Teagasc Marginal Abatement Cost Curve analysis, should be implemented as appropriate. These mitigation options that would deliver reductions of 2.9 Mt CO_2-eq per year, by 2030. The Common Agricultural Policy provides the mechanism for aiding this as it moves to greater national control.
6. There is a need for specific research into mitigation options that are detailed in this paper. Research requirements concern existing mitigation measures, the development of new measures, their technical implementation, impacts or trade-offs and associated development and refinement of inventory accounting methodologies.
7. Adoption and successful implementation of climate change mitigation policy and measures depends on farmers' acceptance based on their lived experience, knowledge and understanding. Additional research and resources to enable effective knowledge exchange are required.
8. Noting the success of participatory approaches to engagement, for example the Citizens' Assembly, a process of co-design could be implemented to facilitate engagement and ultimately strong stakeholder ownership of mitigation policies, which would help to achieve a just transition.
9. Identification and review of existing incentives and schemes that may be in conflict with greenhouse gas mitigation objectives is required, as coherence in policy is vital.

10. Ireland needs to engage with national and international experts to demonstrate and validate its environmental sustainability or ‘green’ credentials regarding food production.
11. Ireland should continue to support research into balance and neutrality concepts while promoting international research and policy development on this topic. Specifically, regarding the development of metrics that appropriately account for the lifetimes of short-lived greenhouse gases, such as methane.

Finally, it is emphasised many of the mitigation measures within the AFOLU sector are likely to bring multiple co-benefits, contribute to economic, social and environmental sustainability and are associated with basic, good land stewardship.

Abbreviations

AD	Anaerobic Digestion
AFOLU	Agriculture, Forestry and Other Land Use
C	Carbon
CAN	Calcium Ammonia Nitrate
CAP	Common Agriculture Policy
CCAC	Climate Change Advisory Council
CCC	The Committee on Climate Change
CH_4	Methane
CICERO	Centre for International Climate Research, Oslo
CLT	Cross Laminated Timber
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
COP	Conference of Parties (to the UNFCC)
CSO	Central Statistics Office
DAFF	Department of Agriculture, Fisheries and Food (former)
DAFM	Department of Agriculture, Food and Marine
DAHG	Department of Arts, Heritage and the Gaeltacht
DCCAE	Department of Communications, Climate Action and Environment
EASAC	European Academics' Science Advisory Council
EBI	Economic Breeding Index
EC	European Commission
EPA	Environment(al) Protection Agency
ESD	Effort Sharing Decision
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
FAO	Food and Agriculture Organisation
FPCM	Fat and Protein Corrected Milk
GHG	Greenhouse Gas
GLAS	Green Low-Carbon Agri-Environmental Scheme

Gt	Gigatonnes (= 10^{13} t)
GWP	Global Warming Potential
GWP*	Global Warming Potential Star
HWP	Harvested Wood Products
IFA	Irish Farmers Association
IPCC	Intergovernmental Panel on Climate Change
kt	Kilotonnes (= 10^{3} t)
LULUCF	Land Use, Land Use Change and Forestry
MACC	Marginal Abatement Cost Curve
Mt	Megatonnes (= 10^{6} t)
N	Nitrogen
N_2O	Nitrous Oxide
NBPT	urease inhibitor - NBPT (N-(n-butyl) thiophosphoric triamide)
NESC	National Economic and Social Council
NFS	National Farm Survey
NH_3	Ammonia
OM	Organic Matter
SEAI	Sustainable Energy Authority Ireland
SOC	Soil Organic Carbon
Tg	Teragrammes (= 10^{12} g)
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WHO	World Health Organisation

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1 INTRODUCTION

In its Annual Review 2018, the Climate Change Advisory Council (CCAC) noted that Ireland was “completely off-course in terms of its commitments to addressing the challenges of Climate Change”. It noted that Ireland’s emissions were rising rather than falling and that under existing and proposed additional measures, Ireland is not projected to meet 2020 or 2030 emissions reduction targets.

Activities within the Agriculture sector are responsible for the largest share of greenhouse gas emissions in Ireland’s emission profile. Methane and nitrous oxide constitute the majority of these emissions. In recent years, agricultural emissions have increased and are projected to continue increasing. This has been due to the expansion of agriculture production, envisaged under to the Food Wise 2025 (DAFM, 2015a) development strategy, the sectoral response to the removal of milk quotas and growing international demand for animal-sourced foods.

The Land Use sector is currently estimated to be a large source of emissions, despite the significant removal of carbon dioxide from the atmosphere to forests and soils. The drainage of organic soils is the main cause of carbon dioxide emissions and occurs across all land uses. Ireland has, over the last century, increased forest cover from about 1% to nearly 11%. At least half of this afforestation occurred since 1980. However, the rate of afforestation has declined in the last decade, and at current rates, Ireland is unlikely to achieve the objective of 18% forest cover by 2046 (DAFM, 2014).

The National Policy Position (Government of Ireland, 2015) takes an integrated approach to Agriculture and Land Use, recognising the relationship between the two sectors in an Irish context and the impact of agricultural and other land management practices on the emissions profile of both sectors.

This working paper follows on from a seminar hosted by the CLIMATE CHANGE ADIVSORY COUNCIL in September 2018, and explores in greater detail the emerging science, mitigation opportunities, potential issues and policy options for the sector. Specifically, this paper aims to inform the council on (i) the Irish AFOLU sector (ii) the associated greenhouse gas emissions profile (iii) possible greenhouse gas mitigation options and (iv) related issues that may require policy development to enable transition within the sector.

Except where otherwise stated, this working paper has adopted Global Warming Potential evaluated over 100 years, GWP_{100}, as the common metric by which the climate impact of emissions of different greenhouse gases are compared and expressed as carbon dioxide equivalent, CO_2-eq. Although the Intergovernmental Panel on Climate Change (IPCC) provided updated GWP_{100} values for methane and nitrous oxide of 28 and 265 (IPCC, 2014a), this report has adopted the values of 25 and 298 respectively are used here in accordance with national and international reporting requirements (Duffy *et al.,* 2019). This is consistent with current reporting and accounting rules under the United Nations Framework Convention on Climate Change (UNFCCC) and European Union (EU) Energy and Climate Package.

2 Setting the Scene

2.1 Agricultural and land use greenhouse gas emissions and removals

Ireland is food secure, but not food independent (Global Food Security Index, 2018). It has developed significant, specialised capacity in grass-based dairy, beef and sheep production. Exports of meat far exceed domestic consumption, while in contrast, Ireland imports a high proportion of the cereals, vegetables and fruit consumed nationally (CSO, 2018c).

Globally, agriculture, forestry and other land use (AFOLU) accounts for roughly 21% of greenhouse gas emissions (FAO, 2016). Three greenhouse gasses are associated with the AFOLU Sector, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Smith *et al.* 2008), accounting for 49%, 30% and 21% of emissions respectively (FAO, 2016). Deforestation is the principal source of CO_2 emissions. With respect to agricultural activities, carbon dioxide emissions are associated with the oxidation of organic matter by microbes in soils or biomass and fossil fuel combustion. Methane emissions are due to enteric fermentation, manure storage, and water table management in rice paddy fields or peatlands. Nitrous oxide emissions arise from management and use of fertilisers, manures and soils (Smith *et al.,* 2008; Schaufler *et al.,* 2010; Renou-Wilson & Wilson, 2018).

Agriculture accounts for approximately 10% of European greenhouse emissions, while European agriculture is responsible for 12% of global agricultural emissions (EC, 2018a). It is estimated that by 2030, livestock production will generate 72% of Europe's agricultural non-carbon dioxide (methane and nitrous oxide) emissions (EC, 2017).

The potential for measures within the Agriculture, Forestry and Other Land Use, AFOLU, sector to mitigate climate change is recognised internationally (Lal 2004; Aertsens *et al.,* 2013; Bustamente *et al.,* 2014, EC, 2018a) and are cost effective. Smith *et al.* (2008) estimated global mitigation potential of AFOLU by 2030 of between 2,500 and 2,700 Mt CO_2-eq yr^{-1} when abatement costs were capped at US$ 50 t CO_2-eq^{-1}. This analysis did not include the displacement of fossil fuels by agriculture, which was estimated to offset a further 2,240 Mt CO_2-eq yr^{-1} (at US$ 50 t CO_2-eq^{-1}).

Table 1 Proportion of Total Emissions derived from Agriculture and Land Use (Source, FAO, 2016; Duffy et al., 2019)

		Gas	Percentage Total Emissions	Percentage AFOLU Emissions
Global AFOLU	Total AFOLU	All	21%	100%
	Carbon Dioxide	CO_2	14%	49%
	Methane	CH_4	42%	30%
	Nitrous Oxide	N_2O	75%	21%
Irish Agriculture	Total AFOLU	All	38% [a]	100%
	Agriculture	All	29% [a]	77%
	LULUCF*	All	9% [a]	23%
	Carbon Dioxide	CO_2	1% [b]	2%
	Methane	CH_4	92% [b]	51%
	Nitrous Oxide	N_2O	93% [b]	24%

[*] LULUCF = Land Use, Land Use Change and Forestry
[a] Total national emissions including LULUCF [b] Total national emissions excluding LULUCF

Carbon sequestration by forestry and grasslands combined were estimated to balance the methane and nitrous oxide emissions across Europe between 2000 and 2005 (Schulze *et al.,* 2009) while Aertsens *et al.* (2013) estimated potential sequestration of 1,566 Mt CO_2-eq yr^{-1} from changes in agricultural practices within the 27 EU member state, equating to 37% of the total CO_2-eq emissions in 2007. However, a number of studies of the impact of the 2003 European heat-wave observed significant emissions of carbon from ecosystems, with Reichstein *et al.* (2013) noting losses equivalent to the carbon sequestration observed in the previous 3-5 years. This sensitivity to extreme events needs to be factored into mitigation policies which rely on significant contributions from carbon uptake due to land use management.

In this paper, the discussion of agricultural emissions is in the context of targets under the EU Energy and Climate Policy. The EU policy treats the Land Use sector separately from both the Emissions Trading System (ETS) sector (which includes energy production and industrial processing) and the non-ETS sector. The non-ETS sector includes activities in agriculture, transport, smaller industries and commercial enterprises, public and residential buildings and waste. Non-ETS sector targets are defined under the Effort Sharing Decision ESD for the period 2013-2020, and Effort Sharing Regulation (ESR) for the period 2021-2030.

Agriculture in Ireland accounted for 32% of national greenhouse gas emissions in 2017 (Duffy *et al.,* 2019) and approximately 44% of non-ETS sector emissions (Lynch *et al.,* 2016b), demonstrating the significance of the sector (DCCAE, 2017). Agriculture is the single largest sectoral emitter (EPA, 2018a). Excluding emission from fossil fuel use, agriculture emitted 19.6 Mt CO_2-eq in 2017 (Duffy *et al.,* 2019). This is compared to the United Kingdom, where agriculture represents approximately 10% of total greenhouse gas emissions (CCC, 2019) and 16% of the non-ETS sector emissions (Lynch *et al.,* 2016b). Denmark has the second highest share of emissions from agriculture at 20.5% in 2017 (UNFCCC, 2019). Irish agricultural emissions in 2017 were 0.24% higher than in 1990 (Duffy *et al.,* 2019), with a negative trend noted from 1998 to 2011. However, emissions have gradually increased since 2011 and equated to a 14% increase by 2017. Emissions increased by 2.8% between 2016 and 2017. This recent trend has been principally attributed to expansion in dairy cow numbers and milk production (EPA, 2018a) with a 2.7% increase in the national dairy cow herd observed between 2017 and 2018 (CSO, 2019).

In the absence of additional mitigation measures, the upward trend in agricultural emissions is projected to continue as a response to market drivers. The EPA have projected a 7% increase from 2017 to 21.1 Mt CO_2-eq in 2030 (without adopting additional mitigation measures), with increases of 22% in the dairy cow herd, 2% in other cattle and 21% in nitrogen (N) fertiliser use by 2030 (EPA, 2018c). Teagasc outlined a baseline scenario where in the absence of new mitigation measures, there would be a 9% increase in greenhouse gas emissions relative to 2005 levels by 2030 (Lanigan *et al.,* 2018; Donnellan *et al.,* 2018).

2.2 IRISH AGRICULTURE AND LAND USE SECTOR EMISSIONS PROFILE

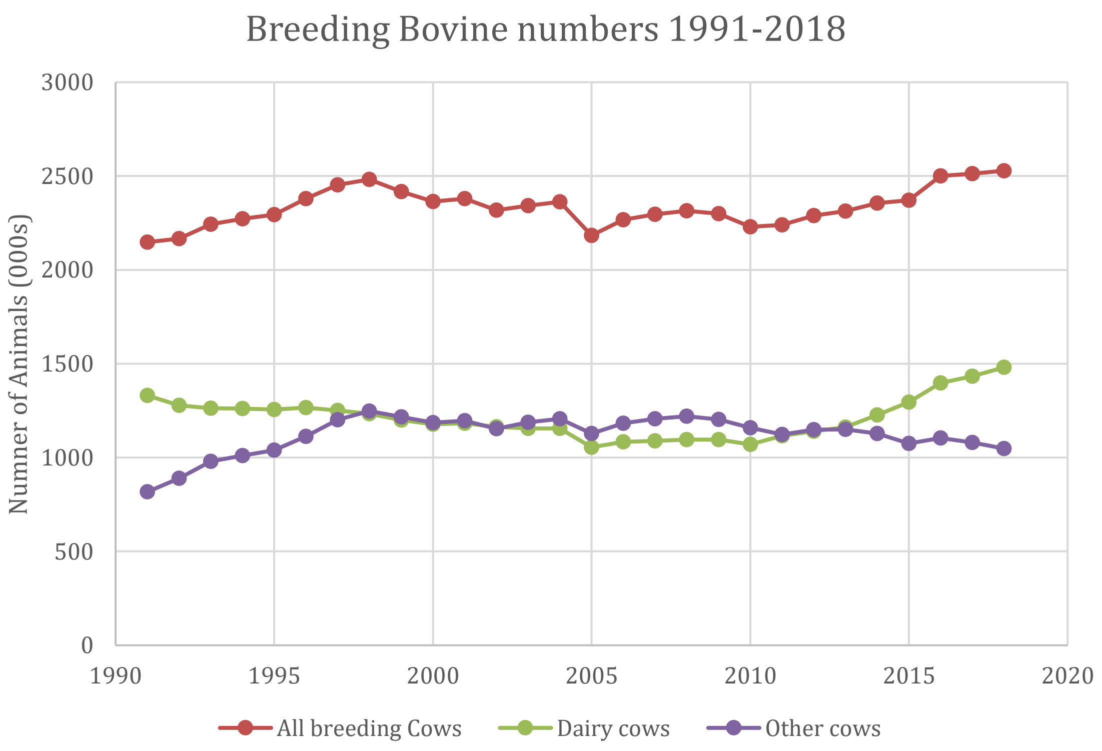
Ireland, which has a temperate oceanic climate (Keane & Sheridan, 2004), is comprised of 6.9 million hectares of which 4.4 million are under agriculture, principally grassland. Managed grasslands and land under rough grazing, accounts for approximately 4.1 million hectares or 93% of the agricultural area (EPA, 2016). The majority of this consists of improved grassland with a smaller area under more extensive management (Sheridan *et al.,* 2017). Arable production accounts for 0.36 million hectares or 8.2% of the agricultural area (EPA, 2016). As of 2018, the national herd stood at 6.9 million animals (CSO, 2019). Historic cattle numbers (June survey numbers) from 1900 are outlined in

Table 2. Since 2011, dairy cow numbers have been gradually increasing, with a 32% increase observed between 2011 and 2018, and currently stand at 1.4 million animals (CSO, 2019). Suckler (non-dairy) cow numbers have gradually declined since 2008 and currently stand at approximately 1.0 million animals, representing a 15% reduction from 2008 levels. However, the recent increase in dairy cows has driven an overall increase in breeding animals, with a corresponding increase in total herd size (Figure 1).

Table 2 Historic cattle June numbers (millions) since 1900 (Source: CSO, 1997; CSO, 2019)

	Year										
	1900	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2005**	**2010**	**2017**	**2018**
Total	3.8	4.3	4.7	6.0	6.9	6.8	7.0	7.0	6.6	7.4	7.3
Cows [a]	1.2	1.2	1.3	1.8	2.0	2.1	2.4	2.3	2.2	2.5	2.5
Other Cattle [b]	2.6	3.1	3.5	4.2	4.9	4.7	4.8	4.6	4.4	4.8	4.8

[a] Includes dairy and suckler cows [b] Includes all replacement heifers, beef cattle and bulls



Note: *Difference between 2004 and 2005 was due to a change in statistical methodology*

Figure 1 Time series of total, dairy and non-dairy cow numbers (Extracted from CSO June Tables).

There were 4.4 million sheep and 1.6 million pigs in 2018, with a decrease in sheep numbers (-3.5%) and slight increase in pigs (0.7 %) nationally since 2017 (CSO, 2019).

Livestock production systems in Ireland rely on grassland, with grazed or conserved grass representing 80 to 90% of the diet of dairy and beef cattle (EPA, 2016).

Historic net greenhouse gas emissions associated with agriculture and land use are illustrated in Figure 2. Agriculture emissions are projected to continue to increase (EPA, 2018c, Lanigan *et al.,* 2018; Donnellan *et al.,* 2018). Methane dominates the Irish agricultural emissions profile, accounting for 66% with nitrous oxide and carbon dioxide accounting for 32% and 2% respectively (Duffy *et al.,* 2019). The EPA identified enteric fermentation (59%), agricultural soils (29%) and manure management (10%) as key emission sources, with minor sources of emissions from lime (1.7%) and urea applications (0.2%) (Duffy *et al.*, 2019). It is worth noting that ruminant enteric fermentation from cattle and sheep alone, was estimated to represent 78% of national methane and 19% of total national greenhouse gas emissions in 2017, while agriculture was responsible for 93% of national nitrous oxide emissions (Duffy *et al.,* 2019).

Ammonia (NH_3) emissions arising from the same agricultural practices are also of serious concern both as an atmospheric pollutant (Donnellan *et al.,* 2018) and major source of indirect nitrous oxide emissions. Atmospheric nitrogen pollution from ammonia is major threat to biodiversity (Kelleghan *et al.,* 2019). Ammonia emissions exceeded targets under the National Emission Ceiling Directive (2001/81/EC) in 2016, directly attributed to increasing livestock numbers and fertiliser use (EPA, 2018d). Agriculture accounts for approximately 99% of national ammonia emissions, of which 90% are associated with the management of livestock manure (EPA, 2018d; Kelleghan *et al.,* 2019; EPA, 2019).

In addition to greenhouse gas and ammonia emissions, agricultural activities have caused considerable localised environmental degradation. Agriculture was identified as responsible for 53% of pollution cases in rivers from 2010 to 2012 (EPA. 2016), primarily responsible for fish kills between 2000 and 2017 (EPA, 2018e), a principle cause of water eutrophication and ground water contamination (EPA, 2018e), while also being the main indirect source of particulate matter in ambient air (EPA. 2016). Agriculture is also identified as both a threat and pressure to biodiversity (DCHG, 2017a) with over 35% of protected habitats highly threatened by agricultural activities (NPWS, 2013).

On the other hand, low-input or extensive agricultural systems are important in maintaining certain habitats and biodiversity (NPWS, 2013; Sheridan *et al.,* 2017) as demonstrated by areas classified as High Nature Value (HNV) farmland (Paracchini *et al.,* 2008; Lomba *et al.,* 2014; Stohback *et al.,* 2015). Martin *et al.* (2016) estimated the likely prevalence of HNV farmland in Ireland, with notably high distribution in Western regions, associated with low-input systems (EPA, 2016).

It should be noted that if negative externalities from agriculture, including greenhouse gas emissions and localised environmental degradation, were quantified in monetary terms and payable by producers, the net economic returns to livestock enterprises would be lower. The imposition of these costs would create the incentive for enterprises to address environmental damage, in order to avoid the cost, and would be consistent with environmental sustainability objectives of the sector.

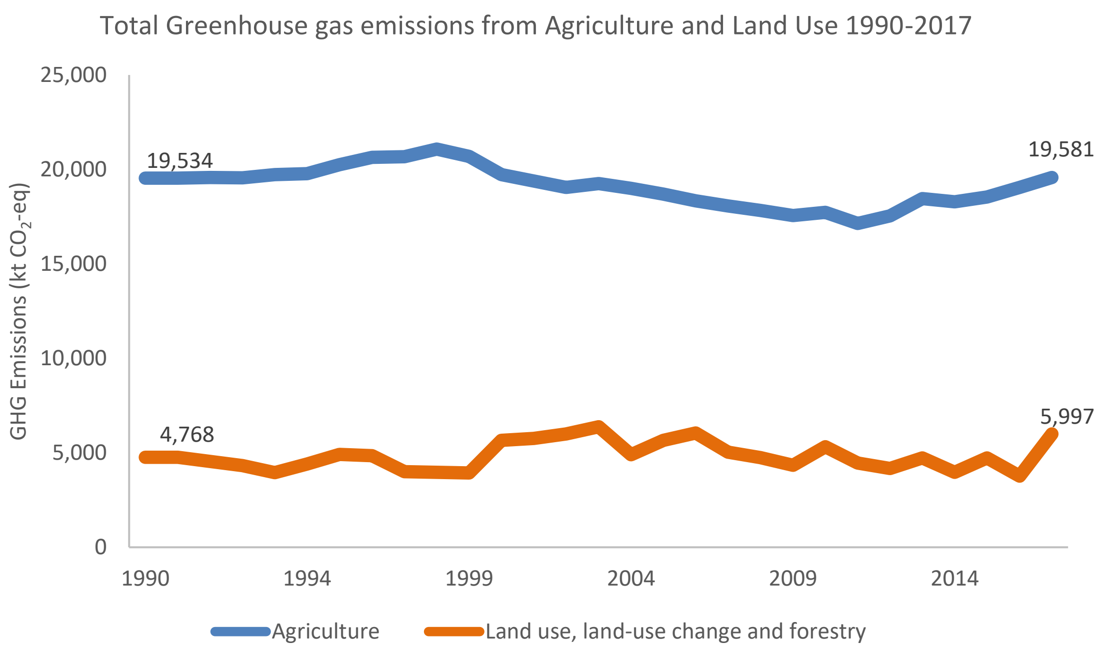


Figure 2 Time series of Net Greenhouse Gas emissions and removals for Ireland

When assessing emissions for land use, the flow diagram shown in Figure 3 illustrates the approach to land use classification for reporting under IPCC guidelines in a hierarchal manner. This ensures consistency of reporting the impact of human management on greenhouse gas emission and removals across all land use categories. The approach aims to ensure that all land types in the country are considered, whilst avoiding double counting.

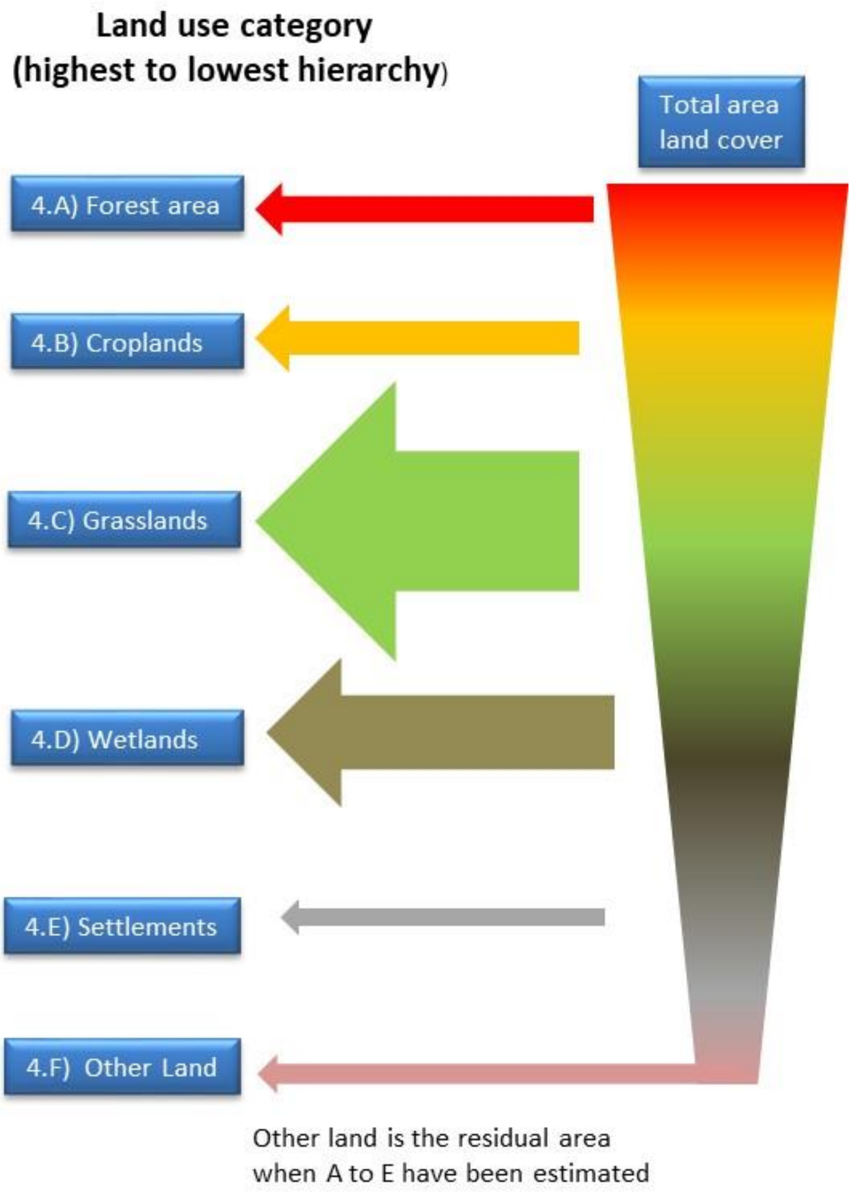


Figure 3 Hierarchy approach to Land Use classification adopted for reporting

Estimates of Land Use, Land Use Change and Forestry (LULUCF) sector emissions and removals are illustrated in Figure 4. In the long-term, the carbon storage capacity of any landscape is finite. However, in many instances the current carbon stocks are not saturated and there may be options to increase sequestration of carbon. In principle, it is also possible to integrate biomass sequestration with carbon capture and storage technologies to enhance the carbon removal potential. However, as yet, these so-called Biomass Energy and Carbon Capture and Storage (BECCS) technologies have not been demonstrated at large-scale and uncertainty remains as to their potential contribution to mitigation. Detailed discussion of key land use types is contained in the Appendix 1. A summary is presented here.

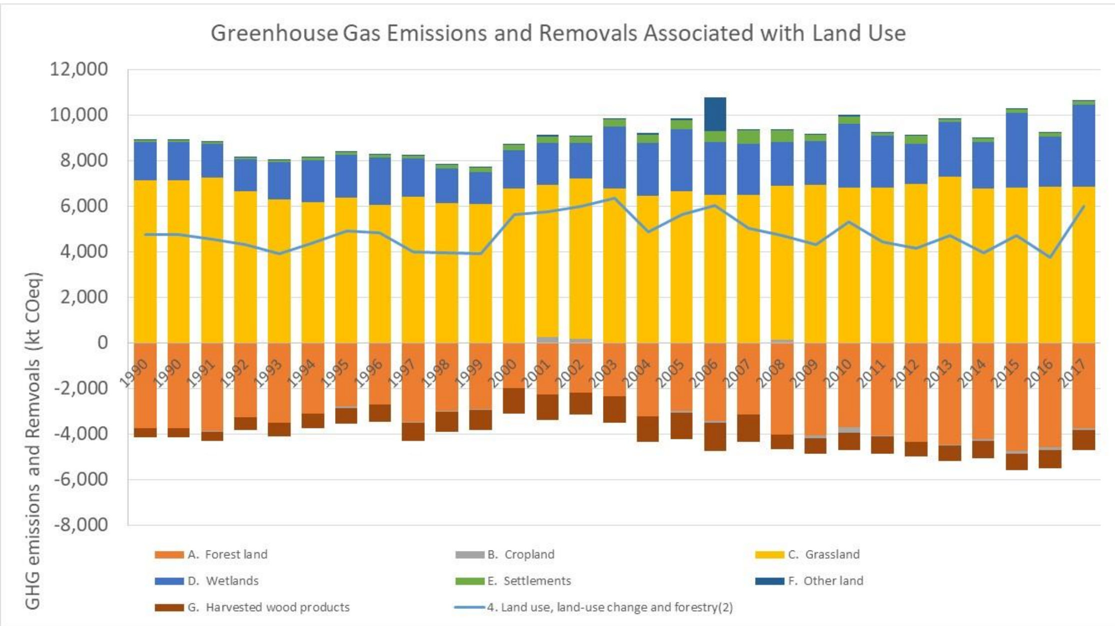


Figure 4 Time series of net emissions and removals associated with Land Use in Ireland

Ireland has one of the lowest proportions of forest cover in Europe with almost complete deforestation of Ireland observed at the beginning of the 20th century. National policy initiatives have increased forest cover from ≈ 1% in early 1900s to ≈ 7% in 1990, to ≈ 11% in 2016 (Annual Forest Statistics, 2018, DAFM). This represents a considerable investment by the State in development of the national forestry sector. The national policy is to increase coverage to 18% by mid-century. To achieve this target, afforestation rates will need to increase significantly, including on agricultural land. Conifers account for 71% of the national stand and deciduous 29%. Ireland's forests are considered relatively young with 45% < 20 years old (DAFM 2018a). Accounting for impact of afforestation or deforestation in National greenhouse gas inventories, only permits changes that have occurred since 1990 to be included.

An average afforestation rate of 7,700 ha yr^{-1} was observed between 2012 and 2017 (DAFM, 2018a), falling to an estimated 4,000 hectares in 2018. Table 3 shows the estimated changes in carbon stock in forest lands between 2006 and 2012. It is worth noting that although the large majority of carbon stock is maintained in the soil, most would not be accountable in the national inventory as much of this carbon was already present in the soil before afforestation. Biomass (including litter and dead wood) accounted for 11.9 and 14.9% of total carbon stocks in 2006 and 2012 respectively. Considering forest area in both years, the carbon stock per hectare in non-soil pools, excluding harvested wood products, increased by 34% between 2006 (58.5 t C ha^{-1}) and 2012 (78.3 t C ha^{-1}). This reflects the maturing of the national forest.

Table 3 Extract from Annual Forest Statistics, 2018, DAFM. To convert between mass of carbon to mass of carbon dioxide multiple by 3.667 (44/12)

Carbon Stock	**2012**		**2016**	
	Million Tonnes	% Total	Million Tonnes	% Total
Above-ground Biomass[a]	30.6	8.9	39.7	10.4
Below-ground Biomass[b]	6.7	1.9	8.8	2.3
Deadwood[c]	1.2	0.4	2.5	0.6
Litter	2.3	0.7	6.3	1.6
Soil	304.9	88.1	323.7	85.1
Total	348.4	100.0	381.0	100.0

[a] Above-ground biomass includes all living stems, branches and needles / leaves based at stump height at 1% of total tree height.

[b] Below-ground biomass includes all roots to a minimum diameter of 5 mm

[c] Deadwood includes all logs, stumps and branches with a minimum diameter of 7 mm

Grassland management is reported as a significant source of carbon dioxide emissions, dominated by emissions of carbon associated with drainage of organic soils (Duffy *et al.,* 2019). Duffy *et al.* (2019) reported emissions from grasslands to be 6.8 Mt CO_2-eq in 2017. Research suggests medium intensity management of grazing lands can enhance soil carbon of mineral soils (e.g. Soussana *et al.,* 2004; Moxley *et al.,* 2014; Hewins *et al.* 2018). However, there is insufficient activity data to provide robust inventory evaluation of this. There is evidence that high intensity management can lead to carbon losses (Soussana *et al.,* 2004; Ward, 2016). Systems such as adaptive multi-paddock (AMP) grazing, which involve high stocking rates over short grazing periods, may increase carbon sequestration (Stanley *et al.,* 2018). There is likely an optimum range of grass-based livestock management intensity to achieve sustainable production, maintain soil function and enhance carbon stocks. The optimum management will depend on farming type, soil type, topography and regional climate (McSherry & Ritchie, 2013). Grasslands occurring on organic soils require different management (Soussana *et al.,* 2004) as discussed in Section 3.2.4.

Croplands account for less than 10% of utilised agriculture area in Ireland. Greenhouse gas emissions are principally associated with soil cultivation and nitrogen fertiliser application. Mitigation measures for croplands include improved nutrient management, the incorporation of straw and the inclusion of cover or catch crops within crop rotations (Eory *et al.,* 2015; RICARDO-AEA, 2016; Lanigan *et al.* 2018). Cover or catch crops are established between principal crops to protect potentially exposed soil over winter months and capture any available soil nutrients, therefore reducing leaching and run-off. Further details are provided in Appendix 1. Due to the comparatively small area under arable production in Ireland, the impact of associated mitigation measures on overall agricultural emissions would be small, but none the less, are an important contribution.

Wetlands in Ireland are a significant source of carbon emissions, due to drainage of peatlands for agriculture, forestry or extraction for power generation, residential heat and horticulture. Peatlands contain up to 75% of Ireland's soil carbon, with carbon dioxide emissions associated with changes in soil temperature, vegetative cover and water table level (Renou-Wilson & Wilson, 2018). It is important to remember that emissions and removals are reported based on current land use, therefore much of the loss of carbon from drained peatlands are reported under grasslands and to a lesser extent forest land. Other studies may classify peatlands on the basis of ecosystem function or ecological status, where drained peatlands may be classified as degraded, regardless of current land use. Based on the Irish soil classification system (Simo *et al.,* 2014) approximately 21% of Ireland or 1.47 million hectares are peatlands (Connolly & Holden, 2009) classified as either ombrotrophic (fed by precipitation and described as bogs) or minerotrophic (fed by springs and described as fens). Raised and blanket bogs account for 311,000 and 774,000 hectares respectively. However, only 10% of raised bogs and 28% of blanket bogs remain intact (DAHG, 2015).

2.3 Drivers within the Agriculture and Land Use Sector

Emissions of greenhouse gases are an inevitable consequence of food production. Demand for food type, quality and volume is influenced by factors including price, income, culture, and other consumer preferences. Production of feed and fodder for animals can also cause significant emissions of greenhouse gases.

Improvements to production efficiency can reduce emissions per unit of product, however there are no mitigation options which can eliminate greenhouse gas emissions completely short of cessation of production.

2.3.1 The Common Agricultural Policy

The Common Agricultural Policy (CAP) in its current format consists of two elements: Pillar I provides direct payments to farmers, known as Basic Payment Scheme; while Pillar II provides further financial incentives for rural development and environmentally sustainable practices.

Farmers are eligible for Basic Payments provided they satisfy of a number of cross compliance standards that include thirteen statutory management requirements and Good Agricultural and Environmental Condition (GAEC) regulations. In addition, a proportion of the Basic Payment represents “Greening” payments which are received following the implementation of specific on-farm measures. Pillar II incorporates measures such as the Rural Development Program which funds the Green, Low-Carbon, Agri-Environment Scheme (GLAS), the Organic Farming Scheme, disadvantaged areas supports and a number of other schemes.

In 2018, the European Commission (EC) published proposals for CAP reform post 2020, covering the period 2021 to 2027 (COM 2018, 392). In this, the EC recognised shifting requirements and challenges within the agricultural sector such as the importance of climate change mitigation in the context of the ambitions set out in the Paris Agreement. The CAP reform proposes a shift in responsibility and design of CAP implementation to Member States, thereby providing potentially greater flexibility and focus in the design of supports. Further discussion on planned changes within the CAP and how these may enable greenhouse gas mitigation within the Irish Agricultural Sector is outlined in Section 3.4.1.

2.3.2 Drivers of greenhouse gas emissions

FoodWise 2025

Foodwise 2025 (FW2025) is an industry led strategy for the development of the agri-food sector in Ireland. FW2025 was published in 2015 and superseded Food Harvest 2020 (DAFF, 2010). FW2025 targets an increase in the agri-food export value by 85% along with a 65% increase in the value of primary production (DAFM, 2015a). The objective of FW2025 is to develop the sector to be achieve economic, social and environmental sustainability. Its successful implementation has been enabled by the removal of the Milk Quota and increased international demand for animal-sourced foods. The value-added focus of FW2025 means, although it was not a direct driver of emissions, it may have resulted in a rebound effect which saw the re-investment of income into production expansion. Environmental sustainability is identified as a core aspect of agri-food sector development, with the ambition that Ireland will become a global leader in sustainable food production (DAFM, 2018b). However, the EPA (2016) has expressed concerns over the delivery of FW2025 targets regarding environmental sustainability, notably around increased greenhouse gas and ammonia emissions.

FW2025 has largely achieved its economic objectives, with significant increase in the value of the agriculture sector (DAFM, 2018b). Much of these gains were achieved through expansion of production, especially in the dairy sector. Despite increased efficiency per unit of product, expansion of dairy production is identified as a principal cause of increases in agricultural greenhouse gas emissions (EPA, 2018a). There is concern over compliance with other environmental targets such as ammonia emissions (EPA, 2016, EPA, 2018d). The Director of Teagasc, speaking before the Committee of Public Accounts, expressed concern about FW2025 regarding increased bovine numbers and meeting 2030 emission reduction targets, suggesting that greenhouse gas mitigation measures "will not be sufficient to off-set" the increase in emissions due to the changes in herd numbers and structure (Houses of the Oireachtas, 2018). Concerns have also been raised over the potential impact of FW2025 on farmland biodiversity (BirdWatch Ireland, 2015), water and soil quality (EPA, 2016).

Indirect Production Support Incentives or Schemes

Although decoupling of CAP direct payments from production was implemented in 2003, a number of support schemes in the beef sector, continued to provide payments in proportion to the number of bovines held on farms (Hanrahan, 2016). Suckler schemes supported expansion of the beef sector following the introduction of the Milk Quota in 1984 (Hennessy & Kinsella, 2013). More recent suckler support schemes include the Suckler Welfare Scheme, Animal Welfare, Recoding and Breeding Scheme (AWRBS) and the Beef Environmental Efficiency Pilot Scheme (BEEPS). The primary aim of more recent schemes has been to enhance the efficiency of production with potential co-benefit for mitigation of greenhouse gas emissions. However, the schemes may have indirectly incentivised the maintenance of livestock numbers.

The Targeted Agricultural Modernisation Scheme (TAMS), which aims to improve the performance and efficiency of on-farm machinery, may also incentivise expansion within dairy enterprises by enabling greater on-farm processing and storage. For example, support is available for milking, milk storage and cooling equipment, as well as in-parlour feeding systems. Other TAMS supports are explicitly focused on achieving improved environmental outcomes, for example supports for low emission slurry spreading equipment, which enable emissions reductions.

The review, monitoring and appropriate modification of agricultural incentives and schemes to avoid conflict and ensure coherence with climate policy is vital. Policies and associated measures should support reductions in absolute emissions in order to contribute to the National Policy objective.

The EU Nitrates Directive permits a maximum application rate for organic nitrogen of 170 kg N ha yr^{-1} (EC, 1991; Statutory Instruments, 2017). This limits the quantity of manure that can be applied, including that deposited to land by livestock itself. It also constrains the number of livestock that can be carried on a particular holding. Authorised derogation from the Nitrates Directive (Statutory Instruments, 2017) allows higher stocking rates provided on-farm measures are taken to avoid pollution but may have enabled dairy production expansion. Derogations are currently under review and could play an important role in ensuring that production is maintained within certain environmental limitations (Government of Ireland, 2019).

Carbon Footprint and Carbon Leakage

Ireland's contribution to global food production is relatively minor, although Ireland is a high net exporter of food. For example, 91% of the beef and veal produced was exported in 2017 (CSO, 2018b). The increase in emissions associated with the expansion of Irish food production to supply export markets (EPA, 2018a; CSO, 2019), has been rationalised on the basis of the low-carbon footprint of Irish production systems and potential for carbon leakage (Lanigan *et al.,* 2018; DAFM, 2018b).

Do Irish dairy and beef production systems have a low carbon footprint?

Life Cycle Assessment (LCA) analysis can be used to estimate the environmental impacts, for example the carbon footprint, of production systems. LCA considering both the inputs and outputs associated with defined stages of a product's 'life' (Finnveden *et al.,* 2009). LCA differs from national inventory accounting (Duffy *et al.,* 2018), which only considers absolute activity emissions and not for specific goods, and those generated within Ireland. Therefore, emissions from processing, manufacturing and distributing potential inputs, for example fertilisers associated with a good, may or may not be included in an LCA study, at the discretion of the researcher.

LCA analysis indicates that temperate grass-based milk production may have a lower carbon footprint compared to other systems in other regions (FAO, 2010; Leip *et al.*, 2010). Some internationally reported values are outlined in Table 4, while Crosson *et al.* (2011) provide a more extensive meta-analysis. It must be remembered that direct comparison between studies is difficult and must be viewed with caution due to what has been included within the methodology that is variations in systems boundaries (Yan *et al.,* 2011).

Of the studies that have compared data from regions or countries using the same methodology., Leip *et al.* (2010) found Ireland had one of the lowest emissions per unit of milk across the EU-27 using LCA analysis (1 kg CO_2-eq kg milk, compared to an average of 1.4 kg CO_2-eq kg milk). In contrast, Lesschen *et al.* (2011), using a different model to LCA, found Ireland had the fourth highest emissions per kg milk across the EU-27 (~ 1.6 kg CO_2-eq kg milk compared to an average of 1.3 kg CO_2-eq kg milk). It is important to note that the studies conducted Leip *et al.,* (2010) and Lesschen *et al*. (2011) used 2004 and 2003 to 2005 data respectively, and therefore may be out of date.

O'Brien *et al.* (2014b) compared high-performance Irish grass-based dairy systems to confinement systems in the UK and the USA using LCA analysis. The confinement systems involved total mixed ration diets and higher concentrate reliance. Irish systems were found to have a 5% and 7% lower carbon footprint than the UK and USA systems respectively. Interestingly, when additional carbon sequestration to grassland soils within the Irish system was excluded, all systems were found to have a similar footprint.

The Origin Green Sustainability Report estimates participating dairy enterprises have an average carbon footprint of 1.1 kg CO_2-eq per kg milk product, but noted large variation in performance between enterprises, from 0.8 to 1.7 kg CO_2-eq per kg (Bord Bía, 2016). Teagasc has estimated average emissions of 0.73 kg CO_2-eq kg milk but varied from ~ 0.68 to 0.80 kg CO_2-eq kg milk for the best and poorest economically performing enterprises respectively. It is important to note that national inventory accounting methodology was used rather than LCA modelling in this study (Buckley *et al.,* 2019), the difference between which has been discussed.

Overall research suggests that Ireland has a relatively low carbon footprint for dairy production. There is clearly room for improvement across the sector, in terms of closing the gap between the best and worst performing producers. However, not all farms will be able to achieve a high level of efficiency, due to local environmental and geographic limitations.

Ireland is the fifth largest beef exporter in the word, exporting principally to Europe (DAFM, 2018b), and estimated to account for 9% of EU beef production (Eurostat, 2018). Beef production systems take various forms globally, including feedlot grain-based or grass-based systems, while stock may come from dairy or suckler herds. The majority of Irish beef is produced by grass-based systems. Leip *et al.* (2010) found

Ireland had the fifth lowest carbon footprint within the EU 27 (19 (as outlined by DAFM, 2018b) kg CO_2-eq kg beef, compared to an average of 22 kg CO_2-eq kg beef) using an LCA approach and based on 2004 data. Using a different approach to LCA, Lesschen *et al.* (2011) found Ireland had the ninth highest carbon footprint within the EU-27 (~ 28 kg CO_2-eq kg beef compared to an average of 22.6 kg CO_2-eq kg beef) using data from 2003 to 2005.

A review conducted by Desjardins *et al.* (2012) indicated that the carbon footprint for some of the main beef production regions (Canada, USA, EU, Australia, Brazil) ranged from 8 to 22 kg CO_2-eq kg of Live Weight (LW). Casey & Holden (2006a) reported 11.26 kg CO_2-eq kg LW yr^{-1} for Ireland and suggested this was similar to beef produced in other EU countries when comparing their results to a limited number of LCA studies available at that time. An overview of recent studies is outlined (Table 5). Crosson *et al.* (2011) provides a more in-depth meta-analysis. It is important to note that values may or may not include impacts from changes in land use or land management as a result of beef production, an important component when estimating carbon footprints (Cederberg *et al.* 2011; Stanley *et al.,* 2018). This highlights the need for caution when comparing studies (Desjardins *et al.*, 2012). For example, an average value of ~ 28 kg CO_2-eq kg carcass weight is described for Brazilian systems, not accounting for land use change. When land use change (deforestation) was included, a value of 726 (±252) kg CO_2-eq kg carcass weight was estimated. However, such land use change concerned 6% of production in 2006, giving an average carbon footprint of 44 kg CO_2-eq kg carcass weight for total Brazilian beef production that year (Cederberg *et al.* 2011).

Table 4 Summary of selected international Life Cycle Analysis outputs reported for the carbon footprint values of milk production systems

Region / Country	Carbon Footprint (CO_2-eq)	Measurement Unit	Source
Global Average	1.5 kg	kg of milk	Hagemann *et al*. (2012)
EU 27 Average	1.4 kg	kg of milk	Leip *et al.* (2010)
Ireland	1.0 kg	kg of milk	Leip *et al.* (2010)
Ireland	1.11 kg	kg of fat and protein corrected milk (FPCM)	O’Brien *et al.* (2014a)
Ireland	0.837 kg (high performance systems)	kg of energy corrected milk (ECM)	O’Brien *et al.* (2014b)

Ireland	Between 0.92 and 1.51 kg	kg of energy corrected milk (ECM)	Casey & Holden (2005)
Ireland	1.06 kg (well drained soils) 1.18 kg (poorly drained soils)	kg of energy corrected milk (ECM)	Sharma *et al.* (2018)
Netherlands	1.4 kg	kg of fat and protein corrected milk (FPCM)	Thomassen *et al.* (2008)
New Zealand	1.0 kg	kg of energy corrected milk (ECM)	Flysjö *et al.* (2011)
Sweden	1.16 kg	kg of energy corrected milk (ECM)	Flysjö *et al.* (2011)
UK	0.884 kg (high performance systems)	kg of energy corrected milk (ECM)	O'Brien *et al.* (2014b)
USA	0.898 kg (high performance systems)	kg of energy corrected milk (ECM)	O'Brien *et al.* (2014b)

The Origin Green Sustainability Report estimates that participating beef enterprises have an average carbon footprint of 11.6 kg CO_2-eq per kg beef liveweight (Bord Bía, 2016). The report also notes the large variation in performance from 5 to 18 kg CO_2-eq per kg. Using national inventory accounting methodology, Teagasc estimated average emissions of 11.9 kg CO_2-eq kg live weight beef. However, values ranged from 9.6 to 14.9 kg CO_2-eq kg live weight beef, for the best and poorest economically preforming enterprises respectively (Buckley *et al.,* 2019).

Table 5 Some internationally reported carbon footprint values of beef production

Region / Country	**Carbon Footprint (CO_2-eq)**	**Measurement Unit**	**Source**
EU 27 Average	22	kg of beef	Leip *et al.* (2010)
EU 27 Average	Between 10.4 and 15.6	kg LW (Suckler)	Desjardins *et al*. (2012)*
Ireland	19	kg of beef	Leip *et al.* (2010)
Ireland	11.26	kg of LW yr^{-1}	Casey & Holden (2006a)
Ireland	13.0	kg of LW yr^{-1} (Conventional)	Casey & Holden (2006b)
Ireland	12.2	kg LW yr^{-1} (Extensive)	Casey & Holden (2006b)
Ireland	11.1	kg LW yr^{-1} (Organic)	Casey & Holden (2006b)

Ireland	13	kg LW (Suckler)	Desjardins *et al*. (2012)*
Brazil	14.3	kg of LW (Conventional)	Desjardins *et al*. (2012)*
Brazil	22.4	kg LW (National)	Desjardins *et al*. (2012)*
Canada (East)	15.3	kg LW (Conventional)	Desjardins *et al*. (2012)*
Canada (West)	8.4	kg LW (Conventional)	Desjardins *et al*. (2012)*
Australia	8	kg LW (Conventional)	Desjardins *et al*. (2012)*
Sweden	11.6	kg LW (Organic)	Desjardins *et al*. (2012)*
UK	25.3	kg of beef carcass (Suckler)	Williams *et al*. (2006)
UK	8.7	kg LW (Conventional)	Desjardins *et al*. (2012)*
USA (Midwest)	14.8	kg LW (Feedlot finished)	Desjardins *et al*. (2012)*
USA (Midwest)	19.2	kg LW (Pasture finished)	Desjardins *et al*. (2012)*

* As outlined in a meta-analysis complied by Desjardins *et al*. (2012).
Please refer to Desjardins *et al*. (2012) for original sources

Therefore, Irish beef production systems appear to have an average to low carbon footprint, though as with studies examining milk, differences in methodology and results make definitive conclusions difficult. However, when compared to non-EU systems while accounting for impacts of land use change, Irish systems have a lower footprint. Similarly to dairy production, there is room for improvement within Ireland and closing the gap between the best performers within the beef sector. As with dairy farms, not all beef farms will be able to achieve a high level of efficiency due to local environmental and geographic limitations at farm scale.

Will a reduction in Irish dairy and beef production lead to a net global increase in emissions?

It is suggested that reductions in beef and dairy production to reduce greenhouse gas emissions in Ireland will result in carbon leakage (Hennessy *et al.,* 2018; Lanigan *et al.,* 2018). Carbon leakage describes the response where a reduction in milk or beef production in Ireland would be compensated by increased production in other countries, where, in addition, production systems may be less greenhouse gas efficient.

Scenario modelling allows the potential extent of leakage to be quantified. Fellmann *et al.* (2018) projected that reductions in EU livestock production would lead to increased production in non-EU countries, limiting the global net benefits of emission reductions within the EU (Fellmann *et al.*, 2018). Considering all agricultural production, leakage was projected to offset 91% of potential emissions reductions achieved within the EU. However, 90% of the resulting emissions generated outside the EU were associated with livestock and animal products suggesting livestock production may be associated with a high leakage effect. Styles *et al.* (2017) indicated that global greenhouse gas emissions may increase if the intensification of UK dairy production led to reduced beef production and an associated international displacement satisfied by low-intensive systems in Brazil. The reduction in beef output from dairy intensification in the UK was assumed due to the same level of milk being produced by fewer cows, resulting in less dairy beef calves.

The leakage rate, which refers to the proportion of an emission reduction achieved in one country that results in increase in emissions in other countries, was examined for Denmark (De ØKonomiske Råd, 2019). Denmark's overall, cross-economy leakage rate was estimated to be between 45% and 53%. However, the leakage rate for agriculture was estimated to be higher, at approximately 75%. This was due partly to food consumption being relatively inelastic to variations in price and income, whereby reduced food production in Denmark would lead to increase food imports. However, this would still represent a net decrease in global emissions, albeit less than the emission reductions reported within Denmark. De ØKonomiske Råd (2019) also noted difficulty in estimating leakage rates for the agricultural sector. This may differ in Ireland as a large proportion of the food produced is exported, therefore, domestic demand for food is not the key determinant of production levels. For this evidence to remain valid in the Irish context, the response of the international markets that Ireland supplies must be considered.

Potential leakage within Europe is constrained by the other EU member states being party to non-ETS emissions reduction targets under the ESR. This may generate demand for imports from non-EU countries. The potential higher carbon footprint per unit of product which non-EU countries have, would lead to increased leakage. Both EU trade policy and non-EU climate policy, may therefore have a considerable impact on leakage potential. EU policy governs imports into the EU, thereby determining the opportunity for a commodity with a potentially higher carbon footprint, to displace those produced in the EU. In terms of non-EU climate policy, individual Nationally Determined Contributions (NDC's) of Paris Agreement signatories, could determine non-EU counties' ambitions towards targets within the sector under their jurisdiction, thereby potentially reducing incentives to increased production to supply EU markets.

The Danish study assumed emission reduction would be largely achieved by a decline in agricultural production. Leakage only occurs from a reduction in activity in one country and displacement in another country. Considering EU agriculture, a study by the Joint Research Council (JRC) indicated that providing subsidies for mitigation measures in agriculture could lesson leakage potential (Van Doorslaer *et al.,* 2015). Subsidised mitigation facilitates emission reductions while ensuring a continued level of competitive agricultural production. However, in this study, more ambitious targets required a reduction in production, increasing the projected leakage.

As far as the authors are aware, no Ireland specific research on emissions leakage has been conducted, except for studies that present leakage as a plausible scenario, when discussing their main findings with respect to production efficiency (Crosson *et al.,* 2011; O'Brien *et al.,* 2014c).

In summary, leakage is likely to occur but there is insufficient evidence to provide a definitive answer to whether a reduction in agricultural production in Ireland will lead to a net increase in global greenhouse gas emissions. The balance of probability suggests that mitigation measures implemented with the support of subsidies, together with an extended range of mitigation options, would not increase global emissions.

Is the rationalisation of current or increased production levels based on production efficiency, avoiding leakage and a net increase in global emissions valid?

Maintenance of current production within the dairy and beef sectors, in the absence of improved efficiency and mitigation, will sustain agricultural greenhouse emissions and potential localised environmental degradation at current levels. Increased production will lead to an increase in agricultural, and non-ETS emissions unless balanced by emission reductions elsewhere and may generate further environmental degradation.

With respect to our national commitments, it must be remembered that EU greenhouse gas emissions reduction targets are based on absolute emissions. The National Policy

Position also aims for carbon neutrality in terms of absolute agricultural emissions. There are no criteria within EU or National policy regarding the efficiency of activities leading to global greenhouse gas emissions, within the agricultural sector.[1] Production efficiency is only relevant in as far as it can lead to reductions in absolute emissions. Leakage is not catered for within the current non-ETS framework. Leakage concerns are addressed in the ETS by issuing allowances to free to exposed sectors.

The leakage argument is only valid when an increase in Irish production displaces less efficient production in other countries. In addition to greenhouse gas emissions, increasing production intensity may negatively impact biodiversity, air and water quality in Ireland (Section 2.2). The drivers for expanded production are international markets and the growing global demand for high carbon intensity products. Supplying growing export markets at the expense of national environmental integrity and reputation, is unwise, regardless of a potential efficiency or leakage. In all cases, agricultural production should occur within local environmental constraints.

Indeed, the Danish Economic Council concluded that despite the effects of reducing agricultural emissions being tempered when accounting for leakage, reductions in agricultural emissions should still be pursued in part due to socio-environmental co-benefits regarding improved water and air quality (De ØKonomiske Råd, 2019)

In conclusion, rationalisation for the maintenance or expansion of the dairy and beef sectors in Ireland based on carbon efficiency, potential leakage and impact on global emissions is not well supported. This is due to; (i) a lack of recent or specific research and differences in findings from studies within the peer review literature, making the potential extent and impact of leakage unclear (ii) current national and EU policy framework not including criteria based on leakage or emissions efficiency in setting

[1] It is worth noting that the EU has established efficiency targets with respect to greenhouse gas emissions from other non-ETS activities such as commercial and passenger vehicles as well as household appliances.

emissions objectives for the sector and (iii) the risk of localised environmental degradation not being addressed under these criteria.

If national and EU policy objectives shift to reduce global rather national greenhouse gas emissions, there may be reason to provide flexibilities and additional supports on sectors with high leakage potential. This approach has been implemented within the ETS sector and may be valid for some non-ETS activities. However, agriculture cannot be exempt from addressing localised environmental degradation or contributing to emission reductions.

2.3.3 Drivers of greenhouse gas mitigation

Efforts to reduce Irish AFOLU sector greenhouse gas emissions are currently guided by (1) a pursuit of carbon neutrality by 2050 and (2) a required 30% reduction (relative to 2005 levels) in non-ETS sector emissions by 2030. The first is the National Policy Position which is consistent with the EU 2050 greenhouse gas low carbon economy roadmap (EC, 2011), while the second is Ireland's agreed contribution under the Effort Sharing Regulation (EC, 2018b) as part of the EU Energy Union and Paris Agreement strategies (EC, 2018c). The National Policy Position on climate action and low-carbon development was published on 23rd April 2014 and the Climate Action and Low-Carbon Development Bill 2015 was published on 19th January 2015 (DAHG, 2015).

National Planning Framework and National Development Plan

The National Planning Framework (Government of Ireland, 2018a) identifies the role of planning and development in providing a mechanism for maintaining and enhancing carbon stocks, especially in the context of forest and peatland protection. This is highlighted again in the Annual Transition Statement (DCCAE, 2018). With regard to agriculture and land use, the National Development Plan is focused on implementation of adaptation measures to manage flooding in vulnerable areas, including nature-based solutions, which would also manage carbon stocks.

National Policy Position and Carbon Neutrality

The Irish Government, following an initial National Economic and Social Council report (NESC, 2012), proposed an approach towards carbon neutrality by 2050 as a policy objective (DCCAE, 2014). Schulte *et al.* (2013) explored the concept of Carbon Neutrality in the context of current reporting and accounting rules. A key finding from this study was that Ireland should consider an “approach towards neutrality” rather than adopt neutrality as an endpoint. Additional research into carbon neutrality commenced in April 2019 with funding from the EPA and DAFM as an action item under the National Mitigation Plan (DCCAE, 2017). Carbon neutrality highlights the potential for LULUCF to mitigate agricultural emissions.

Emissions Targets and Agriculture, Land Use and Forestry

Within the Climate and Energy Package to 2030, land use and forestry are treated separately from the other sectors. Agriculture continues to be considered in the context of agreed national targets for emissions reduction under the Effort Sharing Regulation. Ireland has agreed to a target of 30% emissions reduction (for the non-ETS sector) by 2030 relative to 2005 and has also negotiated access to two flexible mechanisms to enable compliance with this. The first flexible mechanism is essentially a limited transfer of allowances from the Emissions Trading System. The second is limited transfer of credits for removals from accountable LULUCF activities. Access to LULUCF credits are restricted to a maximum of 26.8 Mt CO_2-eq (EC, 2018b) or 5.6% of the non-ETS emissions in 2005. The total removal capacity of LULUCF in the period from 2021 to 2030 is likely to be larger than this, but it assumes the projections of the forest removals are realised and a contribution from the improved management of drained organic soils (Lanigan *et al.,* 2018).

Access to the LULUCF mechanism is contingent on no net loss of carbon from the accountable activities. Where there are source activities within accountable LULUCF activities, then these must be balanced by equivalent removals by other LULUCF activities in the first instance. The available LULUCF removals credits will be the net removal across all accountable LULUCF activities. Even where Ireland out performs in accountable LULUCF activities out to 2030, improvement in land management will contribute towards the National Policy position.

The accounting rules for forestry are complex, but there is confidence that forest land and afforestation will provide significant removals in the period to 2030. Grassland and croplands have less complex accounting rules, with emissions and removals accounted relative to the average during the reference period 2005 to 2009 in other words, reflecting the impact of changes in management relative to the reference period. There is significant uncertainty as to whether changes in land management since 2005 can be documented and whether these will result in a net sources or removals over the period between 2021 to 2030.

Ireland will also need to consider whether to elect to account for changes in wetland management for the period 2021-2030. The potential net removals likely from cessation of peat extraction from Bord na Móna lands are an obvious incentive to elect wetlands. However, the task of providing credible reporting of activities on all national wetlands would be challenging. The additional resources required to achieve this need to be considered in this decision-making process.

The Origin Green Programme

Bord Bía's Origin Green programme is a high-profile initiative that provides supports to farm, manufacturing, retail and food service levels to adopt best practice to enable environmentally sustainable food production. Knowledge transfer, through the Carbon Navigator and other emissions assessment tools, is a core feature of the programme, with voluntary actions and targets for participants. Origin Green also conducts regular audits and data collection on participating farms. The programme has achieved high participation rates with 50,000 beef farms which produce 90% of the beef exported, along with 70% of dairy farms signed up to related schemes. The most recent Origin Green Sustainability Report 2016 (Bord Bía, 2016) outlines significant potential for emissions reduction within beef (7%) and dairy (14%) production based on successful achievement of the individual improvement targets by the cohort of participating farmers. Demonstrating progress in achieving this potential emissions reduction will be important as Origin Green develops.

The IFA/EPA-led Smart Farming initiative complements Origin Green but has a broader environmental scope. The EPA has collaborated with key agriculture stakeholders, including the Irish Farming Association, the Department of Agriculture, Food and Marine, Teagasc, Sustainable Energy Association Ireland (SEAI) and third-level institutions. The aim of the initiative is to enable farmers to adopt sustainable farming practices, including greenhouse gas mitigation measures, through knowledge transfer, while also achieving significant cost co-benefits and improving farm environmental and economic sustainability. In its 2017 report, the Smart Farming programme estimated a 10% average potential greenhouse gas emissions reduction on participating farms while also increasing profitability.

Realisation and verification of the emissions reductions potential under these voluntary programmes requires robust data analysis and monitoring, including commitment to allow access to data and regular, independent assessment and reporting on progress. Data on the uptake of these practices and real world impact on carbon stocks are needed to ensure they are reflected in national reporting of emissions and removals. It must be noted that any failure to meet emission reduction targets or reverse environmental degradation caused by agriculture may have considerable consequences regarding Ireland's international image (Donnellan *et al.,* 2018), greatly undercutting programmes such as Origin Green. The adverse market response and economic impact of reputational damage is difficult to assess but may be greater than the direct cost of non-compliance with greenhouse gas emissions targets, or the marginal costs of implementation of mitigation measures.

Market Trends in Food and Consumer Choice

Ireland exports the majority of the food it produces (DAFM, 2018b) and is dependent on international markets and consumer trends. Diets are changing globally with greater animal-sourced food consumption in developing regions and the encouragement of less animal-sourced food consumption in developed regions.

Fellmann *et al.* (2018) identified changes in consumption of meat as a plausible mitigation strategy within the EU. There is growing recognition internationally that current food systems are exacerbating two growing consumption concerns regarding the delivery of balanced nutritional requirements: under-nutrition contributing to the prevalence of diseases and over-consumption of high-calorie foods contributing to obesity (Friel & Ford, 2015; EASAC, 2017). In addition, food production systems are pushing resource use beyond planetary limits – generating significant global environmental degradation and greenhouse gas emissions. Changes in production and consumption patterns may be required in response to these challenges (Sage, 2012;

Smith & Gregory, 2013; Tilman & Clarke, 2014; EASAC, 2017; FAO, 2018; Willett *et al.,* 2019). The European Academics Science Advisory Council (EASAC) have suggested that reductions in animal-sourced food consumption may improve public health and reduce greenhouse gas emissions as a co-benefit (EASAC, 2017). Friel *et al.* (2009) estimated that a reduction in animal-sourced fat consumption by 30% in the UK could lead to a 15% and 17% reduction in heart disease and premature deaths respectively.

The EAT-Lancet Commission (Lucas & Horton, 2019; Willett *et al.,* 2019; EAT, 2019) recently recommended reduced animal-sourced food consumption in an attempt to define sustainable diets in the context of the UN Sustainable Development Goals and the Paris Agreement. A 50% reduction in the consumption of foods deemed less healthy, including red meat was advocated in conjunction with a 100% increase in consumption of fruit, nuts and vegetables. Similar advice on dietary guidelines was issued by the Canadian Government which recommend higher levels of consumption of plant-based proteins over meat (Health Canada, 2019). In both cases, a reduction but not the elimination of animal-sourced food consumption was recommended. However, the Eat-Lancet Commission also noted difficulty in some regions to satisfy nutritional requirements on plant-based diets, while recognising the dependence of some populations on pastoral based and associated livestock production systems for livelihoods (EAT, 2019). The Global Panel on Agriculture and Food Systems (2016) also highlighted the necessity for animal-based foods, particularly in low income contexts.

Consideration must be given to nutrient requirements of different social groups (EASAC, 2017). There may be cause for a reduction in animal-sourced food consumption at a population scale. However, for certain societal groups including infants, children and women during pregnancy, the consumption of animal-sourced food is preferable in fulfilling critical nutritional requirements, due to its high nutrient density. In low-income situations, nutritional requirements for these societal groups could be difficult to meet without animal-sourced foods (Global Panel on Agriculture and Food Systems for Nutrition, 2016). The satisfaction of critical nutrient requirements from alternative sources such as cereals, may lead to excess energy consumption, promoting obesity. White & Hall (2017) highlighted the contribution of animal-sourced foods in the USA, providing 24%, 48%, 23 to 100% and 34 to 67% of total energy, protein, essential fatty and amino acids respectively. Plant-only diets were projected to cause more nutrition deficiencies, a need for greater intake of food solids and greater excess of energy. Animal-sourced food may provide the most efficient delivery of critical nutrients compared to plant-based foods.

Additionally, from a global food supply perspective, grass-based livestock systems are an efficient use of resources that may not support arable or horticultural production. It is recognised that a “no meat consumption” argument is an oversimplification (Godfray *et al.,* 2010). The FAO projected increased demand for non-staple foods including meat and dairy products in developing regions (OECD & FAO, 2016; FAO, 2017). Godfray *et al.* (2010) also highlighted changes in affluence as a key driver of increased consumption of meat and dairy products, notably in countries such as India and China. Therefore, it is suggested that the impact of trends of lower animal-sourced food consumption in developed regions, may be less than the impact of increased demand for these products in developing regions.

2.4 COMMON METRICS FOR EMISSIONS ACCOUNTING

The issues discussed in this section are important for the long-term transition objective, and an approach towards neutrality. It is important to note that Ireland’s targets for emissions reduction by 2020 and 2030 are accountable in terms of Global Warming Potential evaluated over 100 years, GWP_{100}. Any contributions of carbon emissions and removals within the land use sector to achieving targets will be assessed in the context of existing accounting rules. However, it is open to the Irish Government to use different metrics, including split gas approach, to set domestic targets, distribute the non-ETS burden across sectors, provided that they meet the national target in aggregate in GWP_{100} terms.

Concerns about the use of GWP have been raised both by the scientific community and by some parties to the United Nations Framework Convention on Climate Change (UNFCCC). These concerns have given rise to a renewed focus on the use of GWP within the UNFCCC and among the scientific community. This has resulted in alternative metrics being considered in the scientific literature as reported by the IPCC in its AR5 (IPCC, 2014a). GWP* has emerged recently and seeks to reconcile the impact of emissions of long-lived species, such as carbon dioxide and nitrous oxide, with the on-going emission of short-lived species such as methane. GWP* has the advantage of being a logical extension of previously agreed metrics, but providing the link to policy objectives, namely the stabilisation of global temperature. Allen *et al.* (2016), highlight the equivalence in global temperature response to a once-off, pulse emission of carbon dioxide, and the sustained emission of short-lived gases, including methane. Figure 5 illustrates the long-term impact in a comparison between the pulse emission of 38 Gt CO_2, equal to total global emissions in 2011, and sustained emissions of methane, black carbon and Hydroflourocabons (HCFs). Essentially, the climate impact of long-lived and short-lived species have stabilised by the end of the century. This equivalence can be reflected in a revised interpretation of GWP. The conventional usage of GWP_{100} dictates that the equivalent carbon dioxide of a methane emission is given by:

$$CO_2\text{-eq [tonnes]} = GWP_{100} \times CH_4 \text{ Emission [tonnes]}$$

Using GWP*, the CO_2 equivalence is based on the change in the rate of methane emissions:

$$CO_2\text{-eq* [tonnes]} = H \times GWPH \times \text{change in } CH_4 \text{ emissions [tonnes per year]}$$

where H is the time period and GWPH is Global Warming Potential for a given time period.

The equivalence is determined in terms of temperature change rather than the more abstract integrated radiative forcing. The authors consider this to be more aligned with the objective of the Paris Agreement. They consider a period of H=100 to be consistent with policy relevant timeframes. From this, where GWP_{100} from the IPCC AR5 for methane = 28 (IPCC, 2014a), GWP* would be 2,800, however, the metric only applies to changes in the rate of emission of methane. A sustained increase in the rate of methane emissions is equivalent to a one-off pulse of 2,800 tonnes of carbon dioxide. The opposite is also true, a sustained decrease in methane emissions is equivalent to the removal of carbon dioxide from the atmosphere. In this way, it is evident that the management of sustained emissions of short-lived climate forcers, including methane emissions, is a very important tool for the mitigation of climate change.

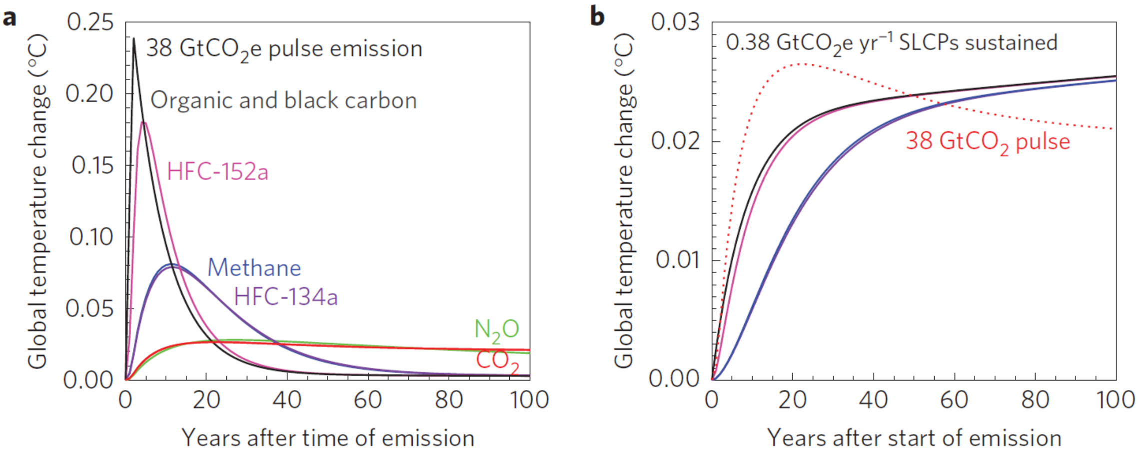


Figure 5 Equivalence between pulse carbon dioxide and sustained change in rate of emission of a short-lived greenhouse gas

The Climate Change Advisory Council requested CICERO (Aamass, 2017) to replicate a study produced for the Norwegian government that estimated the long-term global climate (warming) impact of historic national emissions of the major greenhouse gases.

The study also explored a number of simple scenarios for emissions of carbon dioxide, methane and nitrous oxide and the additional impact of increased or reduced rates of emission on global warming. Figure 6 shows scenarios in which emissions remain constant from 2015 to 2100, and an 80% carbon dioxide emissions reduction by 2050 scenario. The impact of constant methane emissions on global temperature stabilises at approximately 1m°C, on a par with the impact of cumulative carbon dioxide emissions scenario consistent with the national policy position. Figure 7 shows the impact of increased or decreased rates of methane and nitrous oxide emissions on global temperature. It demonstrates that even modest changes in the rate of emission of methane have a notable impact on Ireland's contribution to global change, most remarkable being that a reduction in the rate of emission of methane will reduce Ireland's overall impact on climate.

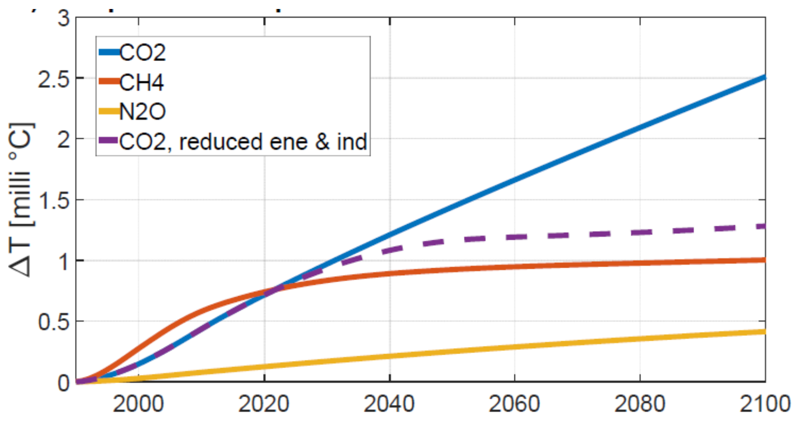


Figure 6 Simple scenario Constant emissions from 2015 to 2100 for carbon dioxide, methane and nitrous oxide and Scenario where carbon dioxide emissions reduce to 80% by 2050

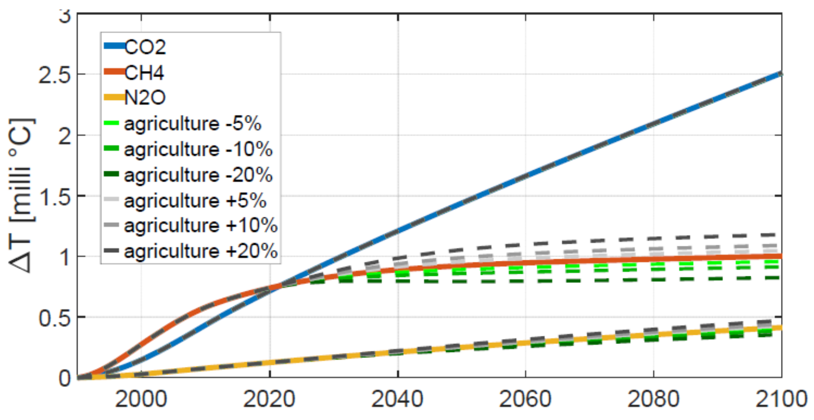


Figure 7 Impact of different rates of emission of methane and nitrous oxide on global temperature

Table 6 Requirement for cumulative removal of carbon dioxide (Mt CO_2-eq) in the period to 2050 and 2100 to balance the temperature response to constant emission of methane and nitrous oxide

Emission scenario for CH_4 and N_2O	**2050**		**2100**	
Cumulative Emissions in Mt CO_2-eq	**CH_4**	**N_2O**	**CH_4**	**N_2O**
Constant CH_4 and N_2O emissions (2016-2100)	-1,300	-220	-1,600	-550
As above, but added 5% from agricultural (Case 7)	-1,400	-230	-1,700	-570
As above, but added 10% from agricultural (Case 7)	-1,400	-240	-1,800	-600
As above but added 20% from agriculture (Case7)	-1,600	-260	-1,900	-650
Historic (1990-2015) + constant CH_4 and N_2O emissions (2016-2100)	-1,600	-430	-1,700	-700

The analysis in Table 6 provides an estimate for equivalent removal of carbon dioxide from the atmosphere required to compensate for constant rates of emission of methane and nitrous oxide at 2015 levels. The table indicates the total cumulative removal of carbon required based on simple scenarios. The area of afforestation required to sequester this mass of carbon in biomass is greater than the total area of Ireland.

An estimate of potential biomass carbon stocks in 1.2 million hectares of forestry land is 260 Mt CO_2-eq, this biomass contained in the entire national forest would balance approximately 16% of warming due to methane emissions from the national herd. This type of long-term analysis highlights the limited capacity of the land sector through sequestration, to balance emissions of long-lived greenhouse gases or the sustained emission of additional short-lived species.

It is worth noting that a reduction in the rate of emission of short-lived species can reverse warming in the medium to long term.

Options on Metrics

In the medium to long-term, it is important that common metrics reflect and support the policy objective in as clear and transparent a manner as possible. The reporting and accounting systems decided at EU and international level are important signals to policy priorities. GWP* is better for demonstrating policy on climate and therefore, is more policy relevant that GWP, due to accounting for short-lived gasses more appropriately. However, it is important to note that the rules and metrics to be used to assess progress towards 2020 and 2030 targets are already agreed at EU level, and during the UNFCCC negotiations at COP24, in Katowice, Poland.

Ireland can continue to support research into balance and neutrality concepts and promote international research and policy development on this topic.

3 AGRICULTURE AND LAND USE MITIGATION OPTIONS

There are no quick fix or single high impact mitigation measures that can achieve profound reduction in greenhouse gas emissions within the Agriculture and Land Use sector. Instead, multiple measures can provide significant cumulative emissions reductions. Moran *et al.* (2011) highlighted the value of establishing a Marginal Abatement Cost Curve (MACC) for policy development in the United Kingdom. Lanigan *et al.* (2018) provide an update to the MACC for Ireland, which detailed 19 potentially cost-effective mitigation measures (< € 50 t CO_2-eq mitigated). The description provided here is not intended to be an exhaustive review, but a brief outline of the most suitable measures currently available for deployment in Ireland following consultation with experts and with focus on those identified as cost-neutral or negative, described as "win-win".

In addition to reducing greenhouse gas emissions, mitigation measures can deliver multiple co-benefits to society, help address negative externalities of agriculture and are therefore linked with environmental, social and economic sustainability. The International Monetary Fund, IMF, has indicated that a shift in the French agri-food system, including the adoption of more environmentally sustainable practices within agriculture, will ultimately bring macro-economic benefits (Batini, 2019).

Mitigation measures are often implemented at farm scale. However, consideration must also be given to impacts of measures at a landscape scale. Farming systems interact with each other and with wider landscape processes, notably water catchments, and therefore the implementation of certain measures should be sustainable at multiple levels. Additionally, farm scale measures are subject to the resources and capacity available to the individual farmer.

Based on technical costs, the Teagasc MACC analysis does not consider the full range of opportunity costs of implementation of mitigation measures. Some mitigation measures, though cost-neutral or negative in direct terms, may be time consuming or require adjusted management and organisation. Such additional resources are difficult to cost appropriately but may dis-incentivise implementation and restrict uptake. Lanigan *et al.* (2018) noted that the indirect cost of measure implementation was not included, for example the establishment of genetic breeding schemes.

AFOLU mitigation strategies are typically divided into three categories; (i) reduction of emissions, (ii) enhanced removal of carbon from the atmosphere and (iii) avoidance of the use of fossil resources (Smith *et al.,* 2008; Moran *et al.,* 2011; Lanigan *et al.,* 2018). Further technical information on individual mitigation measures is provided in Appendix 2. A summary of the mitigation measures and classification of ease of deployment is provided in Tables 9, 10 and 11. Potential mitigation and associated costs are outlined as mean annual values estimated for the period 2021 to 2030 assuming linear adoption, calculated by Lanigan *et al.* (2018) unless specified.

3.1 Reduction of Agricultural Greenhouse Gas Emissions

The majority of the agricultural area of Ireland is under grassland (EPA, 2016; Sheridan *et al.,* 2017) and supporting associated enterprises, notably bovine production (CSO, 2018a; Dillon *et al.,* 2018). Therefore, this section concentrates on mitigation strategies related to bovine systems and grassland management, with limited discussion of options within arable or other livestock production.

3.1.1 Greenhouse gas emissions from livestock

The generation of methane from enteric fermentation is an important agricultural emissions source (Moran *et al.,* 2011). Bovines were estimated to directly produce 10.7 Mt CO_2-eq from methane emissions in Ireland in 2017 or 54.7% of total agricultural emissions (Duffy *et al.,* 2019). When methane and nitrous oxide from associated manure (including both pasture deposition and management) are included, bovines were responsible for 61.3% of total agricultural emissions. Sheep and pigs accounted for 4.1 and 1.7% respectively, including associated manure (Duffy *et al.,* 2019). A number of measures to reduce bovine emissions have been proposed, some of which Teagasc estimated as cost-negative (Lanigan *et al.,* 2018). In all cases, supporting information is provided in Appendix 2.

A Gradual Reduction in Bovine Numbers

As with most mitigation options, a reduction in bovine numbers will have environmental, social and economic impacts and associated co-benefits and trade-offs. Consideration of, and appropriate balancing of these different aspects is crucial.

Dairy production currently is economically sustainable (Dillon *et al.,* 2018) and therefore, there are economic incentives for its maintenance at current levels of activity, or for expansion. Thus, incentives to reduce dairy cow numbers as a mitigation measure, would be costly, entailing high opportunity costs. However, adverse environmental impacts have been observed in intensive dairy regions regarding habitat diversity (Sheridan *et al.,* 2011; Sheridan *et al.,* 2017). On average, dairy production is estimated to be almost two times more greenhouse gas emission intensive per hectare, than beef production (Buckley *et al.,* 2019). Dairy production systems also generate higher nitrogen and phosphorous surpluses per hectare, therefore, all things being equal, generate potentially greater risk of nutrient losses to water courses (Buckley *et al.*, 2019).

In all cases, production should only be within environmental limitations. Further expansion of the dairy herd may increase the risk additional adverse impacts.

The large proportion of beef production enterprises are considered economically unviable (Lynch *et al.,* 2016a; Buckley *et al.,* 2019), with cattle rearing enterprises on average making losses per unit of product at market price (Dillon *et al.,* 2018). Therefore, from an economic perspective, incentives to reduce the national beef herd, through a reduction in the suckler herd, would be more cost effective than to do so in the dairy herd. At farm scale, a reduction in livestock may increase farm income as currently, direct payments appear to support production in suckler farming enterprises (Dillon *et al.,* 2018).

However, from a social perspective and considering the wider rural economy, suckler farming provides socio-economic (Hennessy *et al.,* 2018) and cultural benefits. A rescaling of activity may have significant social consequences and any reduction in numbers should take full cognisance of a just transition (Section 3.4.4). In addition, potential impacts of reduced numbers on the rural landscape must be considered. Extensive suckler farming systems support important habitats (Sheridan *et al.,* 2017) and maintenance of current production may be desirable. A decline or cessation of agricultural activity may negatively impact farmland biodiversity (NPWS, 2013; Strohback *et al.,* 2015). Therefore, caution is required regarding geographic implementation of suckler cow numbers reductions.

From a greenhouse gas emissions perspective, the impact of a gradual reduction in national suckler cow numbers and stabilisation of the dairy herd, in the absence of other agricultural mitigation measures, can be explored through the following simple scenarios for the period out to 2030. EPA national inventory methodology and Irish country specific emission factors were used.

Scenario A

- The dairy herd is maintained at 2018 levels
- The suckler herd declines by 15% relative to 2018 levels

Over the last decade (2008-2018), the suckler herd has been steadily declining at an average rate of approximately 1.4% per annum. If this trend continues, suckler cow numbers would fall by approximately 15% by 2030, relative to 2018. In this scenario, total agricultural greenhouse gas emissions would be 19.2 Mt CO_2-eq in 2030, or 1.7% less than 2017 and 2.9% above 2005 levels (Table 7). This estimate considers the associated reduction in replacement heifers (followers) and cattle in different age classes, along with altered nitrous oxide emissions from manure management and reduced livestock manure deposition. Fertiliser use was assumed to stabilise at projected 2018 levels, due to a lack of demand from the dairy sector. Sheep numbers in 2030 were assumed to reduce by 45% and total pig numbers by 17% relative to 2005, in accordance to Teagasc baseline projections (Lanigan *et al.,* 2018; Donnellan *et al.,* 2018).

Scenario B

- The dairy herd is maintained at 2018 levels
- The suckler herd declines by 30% relative to 2018

In this scenario, total agricultural greenhouse gas emissions would be 18.5 Mt CO_2-eq in 2030, or 5.4% less than 2017 and 0.9% less than 2005 levels (Table 7). It is worth noting that this level of reduction within the suckler herd is approximately the level of reduction suggested in the Teagasc baseline (S1) emissions projection for 2030.

Again, this projection accounts for reductions in replacement heifers (followers), cattle in different age classes and nitrous oxide emissions from manure. The national sheep flock was assumed to reduce by 45% and the pig herd by 17% compared to 2005 levels in

2030 (Lanigan *et al.* 2018; Donnellan *et al.,* 2018). Fertiliser use was assumed to stabilise at projected 2018 levels.

Scenario C

- The dairy herd is maintained at 2018 levels
- The suckler herd declines to pre-Milk Quota (1984) levels

This scenario explores the reduction required to reduce the suckler herd to 1984 levels (~ 479,000 cows), the year the Milk Quota was introduced. To reach this level by 2030, it is estimated that approximately a 53% reduction in suckler cows, would be required, relative to 2018. With this reduction and in conjunction with the stabilisation of the dairy herd at 2018 levels, total agricultural emissions in 2030 are projected to be 17.4 Mt CO_2-eq in 2030 or 6.7% less than 2005 levels and 10.9% less than 2017 levels (Table 7).

As with Scenarios A and B, reductions in replacement heifers, cattle of different age classes and manure nitrous oxide emissions are accounted for. Sheep and pig baseline projections outlined by Lanigan *et al*., (2018) and Donnelan *et al*. (2018) were included.

Table 7 Summary of some projected impacts from gradual reductions in suckler cow numbers

	2005	**2017**	**2018[a]**	**2030 Scenario A**	**2030 Scenario B**	**2030 Scenario C**
Dairy cows (000s)	1,025	1,388	1,425	**1,425**	**1,425**	**1,425**
Suckler Cows (000's)	1,121	1,050	1,015	**863**	**711**	**479**
Total Cattle (000's) [b]	6,951	7,306	7,402	**7,002**	**6,594**	**5,973**
Bovine enteric fermentation CH_4 emissions (kt CO_2-eq)	9,840	10,720	**10,855**	**10,537**	**10,005**	**9,193**
Bovine Manure CH_4 emissions (kt CO_2-eq)	925	999	**1,010**	**960**	**910**	**835**
Total agricultural emissions (kt CO_2-eq)	18,699	19,581	**19,919**	**19,244**	**18,531**	**17,445**

Data Source: CSO, 2019; Duffy *et al.,* 2019 and EPA inventory methodologies.
All projected figures are outlined in blue.
[a] 2018 emission values were not available at the time of publishing and therefore projections are outlined.
[b] Total cattle numbers differ from CSO figures due to differences in accounting methodology used within EPA emissions inventories. As these scenarios explore impacts on emissions, EPA inventory methodology was employed.

Gradual number reductions could, as and where appropriate, result from re-structuring, re-scaling, extensification of intensive systems or diversification within existing enterprises. For example, re-structuring could include greater integration between dairy and beef systems through contract rearing or enhanced dairy-beef production, therefore potentially releasing land from beef production or reducing the requirement for suckler cows. The newly developed Dairy Beef Index may enable restricting of the sector (ICFA, 2018). The carbon footprint of dairy-beef production was found to be considerably lower than from suckler-beef production (Casey & Holden, 2006a). The extent to which integration can occur requires research. Changes to the CAP may enable other options (Section 3.4.1). CAP could be designed to encourage extensification of intensive systems, with part of basic payments subject to a maximum stocking density. This may bring environmental co-benefits on farms with currently high stocking densities. The scope for extensification within suckler systems requires research. Farms that already have low stocking densities, potentially supporting HNV farmland (Martin *et al.* 2016; EPA, 2016), should automatically qualify, with little or no adjustment in management. Further extensification in such situations may negatively impact biodiversity (NPWS, 2013) and should be avoided. Similarly, the diversification of enterprises, and potentially exiting bovine production should happen with cognisance of environmental impacts.

As indicated by Scenarios A, B and C, a gradual reduction in numbers would significantly contribute to reducing overall agricultural emissions, enabling additional mitigation measures in combination, to potentially achieve emission reduction targets. It is recognised that the proposed mitigation measures alone are insufficient in meeting targets (Lanigan *et al*., 2018).

In discussion with experts, several potential options to encourage reductions have been proposed including: sectoral emissions trading, retirement schemes for suckler cows and as discussed, coupling farm payments to environmental / ecosystem service provision. The latter could involve payments to support the measured delivery of alternative ecosystem services, other than agricultural production. Production or consumption taxes were discussed but thought to be controversial with low public acceptance. Additionally, the high proportion of food exported would make implementation challenging. Regarding social aspects, it is critical that just transition is pursued. Clearly, comprehensive research is required and regrettably beyond the scope of this working paper.

Extended grazing season

Conserved grass, e.g. silage, may contain more lignin or cellulose than fresh grass. The digestion of higher levels of cellulose is associated with increased methane emissions (Boadi *et al.,* 2004). Extending the grazing season may increase the level of fresh grass consumed and reduce conserved grass intake during housed periods. Additionally, a reduction in livestock housing periods may reduce the quantity of stored manure, further reducing methane emissions. Lanigan *et al.* (2018) estimated reductions of 0.065 Mt CO_2-eq as a result of extended grazing at a negative cost of -€96 t CO_2-eq abated per annum facilitated by altered grazing management or improved soil drainage. Issues may arise on vulnerable soils.

Dietary additives and vaccines

Bovine dietary additives, supplements and vaccines may also reduce methane emissions though products are in the early stages of development and require further research. Research into enzyme inhibitors (for example 3-nitrooxypropanol (3-NOP)) has shown promising results. There are potential issues regarding administration within grass-based systems where opportunities for feeding may be limited. The development of vaccines, which induce an immune response to produce antibodies that inhibit methanogens, may negate the need for as regular administration, but appears challenging. Research into the use of additives and vaccines within Irish bovine systems and their potential sides effects is required.

Genetic Efficiency

Breeding indices such as the dairy Economic Breeding Index (EBI) and beef sector equivalents may be used to help increase favourable genetic traits associated with reduced greenhouse gas emissions in livestock. For example, traits associated with feed intake, methane emissions, daily live weight gain and animal health may help increase production efficiency. Improved beef animal maternal traits were estimated to mitigate 0.025 Mt CO_2-eq at a cost of -€602 t CO_2-eq abated per annum, improved beef terminal traits, 0.061 Mt CO_2-eq at -€215 t CO_2-eq per annum and improved dairy traits, 0.43 t CO_2-eq at -€200 t CO_2-eq per annum (Lanigan *et al.,* 2018). However, any reductions in emissions are dependent on cattle numbers remaining static as any expansion will offset genetic efficiencies of individual animals.

Herd Health

Endemic diseases and poor animal welfare impact livestock production efficiency. Ensuring herd health allows optimal utilisation of feed, reduces finishing times, enhances output per animal and ensures optimum calving intervals, which combine to achieve a potential reduction of greenhouse gas emissions in absolute terms and per unit of product. Additionally, greater animal survival rates impact absolute emissions. Overall improved herd health was estimated to mitigate a total of 0.131 Mt CO_2-eq per annum at a negative cost of -€46 t CO_2-eq (Lanigan *et al.,* 2018).

Mitigation Option 1. - Reducing bovine emissions

A reduction in national bovine numbers may be necessary. Lanigan *et al.* (2018) identified cost effective bovine mitigation options, which would aid emissions reductions. These combined with a continued gradual reduction in the suckler herd in conjunction with stabilisation of dairy cow numbers, would represent an important contribution to national efforts to reach Effort Sharing Regulation targets. Incentives and supports could be refocused to facilitate this and achieve environmental and social objectives, while avoiding adverse impacts to farm enterprises and the wider rural economy. Any encouraged reduction of the suckler herd should only happen where appropriate, with full cognisance of local environmental impacts and just transition.

3.1.2 Greenhouse gas emissions from soils

Soil management can lead to emissions of all three key greenhouse gases (carbon dioxide, nitrous oxide and methane) (Schaufler *et al.,* 2010) and are determined by factors including, soil moisture content, temperature, pH, site characteristics, vegetative cover and the availability of nutrients (Oertel *et al.,* 2016). The sequestration of carbon dioxide is discussed in the next section.

Soils are a principle source of nitrous oxide emissions and direct emissions are estimated based on the availability of nitrogen from fertiliser and manure application rates and from grazing livestock excretion rates (Butterbach-Bahl *et al.,* 2013; Bauwman *et al.,* 2013; Duffy *et al.,* 2019). Duffy *et al.* (2019) estimated direct nitrous oxide emissions from agricultural soils in Ireland to be 5.1 Mt CO_2-eq in 2017 and represented 26.3% of total agricultural greenhouse gas emissions.

Nitrogen fertiliser formulation

The substitution of Calcium Ammonium Nitrate (CAN) fertiliser with protected urea was found to reduce nitrous oxide emissions on grasslands by 70% (Harty *et al.*, 2016) without yield penalties (Forrestal *et al.*, 2017). Protected urea is currently commercially available at approximately the same price as CAN. Teagasc estimated a reduction in emissions of 0.52 Mt CO_2-eq yr^{-1} from the substitution of CAN with urea, at a cost of €8 per t CO_2-eq abated (Lanigan *et al.,* 2018). This measure is included despite incurring a cost, as the potential reduction in nitrous oxide emissions is considerable. The use of protected urea, which contains a urease inhibitor, typically NBPT will also limit ammonia emissions that are associated with the use of urea. However, concerns over the potential fate of NBPT residues within the food chain have been raised. Following a thorough review of literature, Teagasc suggested these concerns were unfounded. Empirical research is currently being conducted by Teagasc to confirm this conclusion. Further information can be found in Appendix 2 (Section A.2.1). The European Union Good Agricultural Practice for Protection of Waters (GAP) regulations allow the Minister for Agriculture, Food and the Marine to specify what nitrogen fertiliser formulations are permitted for use on farms with high stocking rates from January 2021 (Statutory Instruments, 2017). This provides a mechanism for legally requiring the replacement of CAN with protected Urea on certain farms.

Mitigation Option 2. - Nitrogen fertiliser formulations

Protected urea can substitute for CAN within the Irish beef sector with immediate effect, while it is prudent to await the findings of research on residues before progressing to the substitution of CAN with protected urea in dairy production systems, which typically employ more intensive fertiliser strategies. Research indicates that the use of protected urea-based fertilisers is very effective at reducing both nitrous oxide and ammonia emissions, the latter a major pollutant and an indirect source of additional nitrous oxide. Protected urea is currently commercially available at approximately the same price as CAN. Despite anecdotal concerns, there is currently no evidence that NBPT residues enter the food chain, Teagasc is currently undertaking additional research to confirm this. Nitrates regulations provide an opportunity to ensure some replacement of CAN with protected Urea.

Nitrogen fertiliser replacement by multi-species swards

The use of multi-species swards which include clover and forage herbs have been shown to reduce nitrogen fertiliser requirements. Research in Ireland suggests comparable yields can be achieved with multispecies swards receiving 40 to 90 kg N ha^{-1} yr^{-1} as intensively fertilised monoculture swards receiving up to 250 kg N ha^{-1} yr^{-1}. Nationally, farm surveys have demonstrated significant scope for the establishment of multispecies swards. Lanigan *et al.* (2018) estimated annual emission reductions of 0.069 Mt CO_2-eq a cost of -€7 per t CO_2-eq abated from avoided fertiliser usage where 25% of beef and 15% of dairy farms included clover in swards by 2030.

Mitigation Option 3. - Multi-species swards

Research in Ireland indicates that acceptable yields can be achieved with reduced nitrogen fertiliser with the use of clover. Further research into multi-species swards should be conducted under ‘real-life’ on-farm conditions to understand impacts and develop best management advice. The inclusion of clover and herbs within swards not only reduce fertiliser requirements and nitrous oxide emissions, but also generates a number of co-benefits including the enhancement of livestock health and performance, and potentially, sward drought resistance. Grassland research in Ireland over the last 60 years has concentrated on optimising ryegrass systems. Better understanding of the management of multi-species swards is required.

Soil fertility management

There is a need to maintain soil fertility of productive farmlands within an optimum range to ensure healthy soil function and plant performance. Soil testing and information on soil fertility correction is a fundamental service provided by agricultural advisory services. Research and advisors are unambiguous on the need to improve soil condition and the resulting benefits to profitability and environmental sustainability. However, Teagasc estimates that 88% of Irish grassland soils have suboptimal pH, potassium (K) or phosphorous (P) levels (Plunkett, 2018). It is believed that this has led to the over-application of nitrogen fertiliser to compensate for the lack of fertility in an attempt to maintain productivity – leading to unnecessary costs and adverse environmental outcomes, including additional nitrous oxide emissions. Lanigan *et al.* (2018) proposed a scenario where appropriate pH management through lime application occurred on an a third of grassland with sub-optimal pH (429,000 hectares). This was estimated to increase the nitrogen availability equivalent to the application of 30,000 t N over the period 2021 to 2030, mitigating 119.6 kt CO_2-eq from reduced nitrous oxide emissions. This more than compensates for the emission of carbon dioxide associated with lime application, in this example estimated to be 6.8 kt CO_2-eq. The estimated net mitigation over the period 2021 to2030 was 1.12 Mt CO_2-eq at a negative cost of -€124 per t CO_2-eq. The EPA, in submission to DAFM on nitrate derogation, has recommended that optimal soil pH should be maintained on derogation farms.

Mitigation Option 4. - Soil fertility management

There are few technical barriers to improving soil fertility as techniques such as liming are well established and understood. Soil testing and information on soil fertility correction is a fundamental service provided by agricultural advisory services. It is necessary to review options to enhance the effectiveness of national programmes to improve soil fertility in Ireland. Research may be necessary to explore underlying barriers to implementation.

Low emission slurry spreading

Spreading of animal slurry on agricultural lands is an important means of nutrient recycling. However, the application of slurry also results in the emission of greenhouse gases and ammonia. The technology used for application greatly influences the amount of emissions. Splashplate spreading is the most common technology currently in use in Ireland but results in high rates of emission. Alternative, low emission slurry spreading technologies (LESS) exist including trailing shoe, and band spreading. Appropriate use of LESS systems also reduce indirect nitrous oxide emissions while improving fertiliser replacement value of slurry, potentially reducing nitrogen fertiliser requirements, further nitrous oxide emissions and lower input costs. Lanigan *et al.* (2018) estimated an annual mitigation of 0.117 Mt CO_2-eq at a cost of €187 t CO_2-eq assuming 50% of the slurry applied was spread by low emission systems. The implementation of low emission technology is expensive if only greenhouse gas abatement is considered. However, it is included in this report due to the significant co-beneficial impact on ammonia emissions. Grant aid through TAMS is available for farmers to purchase equipment. Uptake of these grants is strong, but additional supports may be necessary to achieve widespread deployment.

Mitigation Option 5. - Low emission slurry spreading

Low emission slurry spreading reduces ammonia and therefore, indirectly nitrous oxide emissions. The associated equipment is expensive. Support for the acquisition of equipment through TAMS is available to farmers. Uptake of these grants is strong, but additional supports may be necessary to achieve more widespread deployment.

Soil structure management and drainage of mineral soils

Soil structure refers to the physical arrangement of soil aggregates and the corresponding porosity within the soil matrix. Soil structure is recognised as underpinning overall soil quality, directly and indirectly influencing many soil processes, including productivity and greenhouse gas emissions. Soil structure is easily damaged by processes such as compaction on grassland and arable soils. Soil compaction may result from livestock or machinery traffic, notably when soils are wet and create favourable conditions for nitrous oxide emission. There is a risk that extended grazing practices may inadvertently cause compaction. Increased awareness and therefore prevention can be provided through the advisory services.

A significant proportion of agricultural soils in Ireland exhibit restricted drainage. Wet soil conditions provide favourable conditions for enhanced nitrous oxide emissions. Therefore, improved drainage can prevent nitrous oxide production as well as increasing a soils resistance to compaction. Drainage management can be costly and requires expert advice, as where implemented incorrectly can be ineffective. Teagasc proposed a scenario where the improved drainage of 10% of the total area of grassland (with linear uptake in the period 2021- 2030) would reduce nitrous oxide emission by an average of 0.197 Mt CO_2-eq yr^{-1} at a cost of €16.2 t CO_2-eq. Though not cost-neutral, drainage has been included due to its potential co-benefits regarding production, soil structure stability and enabling additional greenhouse gas mitigation through extended grazing seasons.

Mitigation Option 6. - Soil structure and drainage

Improved knowledge transfer on soil structure management from farm advisory services is required, particularly where extended grazing is encouraged. Improvements in drainage can reduce greenhouse gas emission but should be undertaken on the basis on expert advice and on a site-specific assessment.

3.2 Carbon stocks and sequestration potential in soils and biomass

3.2.1 Carbon stocks and sequestration potential in grasslands

Irish grasslands are estimated to contain 53% of national soil carbon stocks or 769 (± 163) Tg C in the top 50 cm of soil (Xu *et al.,* 2011). A large proportion of this carbon is held in relatively stable forms (Kiely *et al.,* 2009). The Royal Irish Academy (RIA, 2016) indicated that Irish grasslands have potential to sequester additional carbon. However, research is required to determine the best management practices to maintain and enhance carbon stocks in mineral soils. Studies suggest that grazing and nutrient input intensity levels can be optimised to enhance stocks, above or below which carbon losses may occur. The grazing management to enhance soil carbon stocks should only be achieved within the carrying capacity of the land with respect to other environmental impacts. Lanigan *et al.* (2018) outlined potential management options regarding the balance of carbon and nitrogen inputs. Improved management of 450,000 hectares was estimated to sequester 0.262 Mt CO_2-eq annually at a cost of €45 per t CO_2-eq. It must be noted that there is a limit to the sequestration that can occur, due to soils reaching a maximum carbon storage capacity. Management of grasslands on organic soils is discussed in Section 3.2.4.

Mitigation Option 7. – Carbon stocks and sequestration in mineral soil grasslands

Grasslands are a significant stock of soil carbon in Ireland. It is recommended that long-term in-field research be conducted into the impacts of grassland management on carbon sequestration considering sward species composition, grazing intensity and nutrient inputs. It is additionally recommended that associated activity data and country specific land use and management factors for national inventory reporting are developed.

3.2.2 Forests and Woodland

Carbon sequestration by afforestation

Forests are recognised as an important store of carbon. Afforestation is identified as a key emissions mitigation strategy. A mean annual afforestation rates of 7,674 ha yr^{-1} was observed between 2012 and 2017 (DAFM, 2018a), though current rates may be as low as 4,000 ha yr^{-1}. These rates are well below the annual requirements of 10,000 hectares to meet a target of 18% national forest cover nationally by 2050. Lanigan *et al.* (2018) estimated that an afforestation rate of 7,000 ha yr^{-1} could mitigate on average, 2.1 Mt CO_2-eq annually, at a cost of €45 per t CO_2-eq abated. However, low afforestation rates as well as deforestation and existing plantation reaching harvestable maturity may limit the accountable removals in the period beyond 2030. Teagasc have identified barriers to afforestation including social perceptions and a rigidity in afforestation schemes regarding the permanent re-classification of land as forest notwithstanding current flexibility within the schemes.

Mitigation Option 8. - Afforestation

The redesign of incentive schemes to enable higher afforestation rates may be necessary. Insights from Teagasc social research may provide a guide to redesign and appropriate targeting of afforestation incentives to increase implementation. Current afforestation rates are considerably below national targets, limiting the likely contribution that forestry will make to mitigation of national greenhouse gas emissions in the period to 2050.

Carbon sequestration by agroforestry

Agroforestry refers to the integration of trees within either livestock or crop production systems. Low-density planting of trees within grassland systems increases land functionality, carbon sequestration (both above and below ground), enhances the natural environment and improves nutrient catchment potentially limiting nitrous oxide emission. Agroforestry may also enable extended grazing due to modified soil structural and associated hydrological properties, while providing additional shelter for livestock. Agroforestry systems are generally less productive than conventional systems, but can offer alternative income opportunities with respect to biomass and wood harvest. Carbon sequestration rates are site and species specific but typically range from 1 to 6.5 t C ha^{-1} yr^{-1} with 2 t C ha^{-1} yr^{-1} considered reasonable for the introduction of agroforestry on temperate grasslands (Aertsers *et al.,* 2013). Research in Northern Ireland showed agroforestry led to more stable forms of soil organic carbon (Fornara *et al.,* 2017).

Agroforestry allows the continuation of conventional agricultural activities, making the system more appealing to farmers. However, existing incentives for agroforestry require the permanent reclassification of land as forestry. This may act as a disincentive to the adoption of agroforestry in Ireland. Additionally, market outlets for associated wood product, may be limited.

> *Mitigation Option 9. - Agroforestry*
>
> Agroforestry has the potential to contribute to greenhouse gas mitigation and adaptation to the impacts of climate. Redesign of agroforestry incentives to maintain classification of land as agricultural could address barriers to adoption. Research into market outlets for associated wood products is required.

Small-scale native woodland plantations

Forestry grants permit small-scale afforestation, with a minimum area of 0.1 hectares for deciduous plantations (DAFM, 2015b). It is suggested that an agricultural scheme to promote small-scale native deciduous plantations on farmland could be established. Such plantations would bring multiple benefits including carbon sequestration and enhancing the natural environment and ecosystem service provision, with commercial value in the long-term. Schemes for native woodland plantations could be specifically directed to farms under intensive management (e.g. dairy farms) or in regions with low woodland coverage. Plantation of a percentage area of each holding (not under existing hedgerows or scrubland) could be required under CAP Pillar II schemes, with the option of reducing the area if other greenhouse gas mitigation measures are successfully adopted. Research is required into the potential area for such plantations, their likely contribution to greenhouse gas mitigation, the environmental impacts - regarding intensification or increased stocking rates on remaining un-planted land, and economic impacts - from potentially reduced production.

> *Mitigation Option 10. - Small-scale native woodlands*
>
> Agricultural grants should be made available for promoting the planting small areas of farmland with native deciduous trees. Such schemes could require planting of an area

percentage of holdings under intensive management. The required area could be reduced on the successful implementation of other greenhouse gas mitigation measures; thereby ensuring on-farm mitigation at some level. Research is required into the likely greenhouse gas mitigation capacity, wider environmental and economic impacts, along with the potential markets for wood products produced.

3.2.3 Carbon sequestration by farm hedgerows

Hedgerows represent an important carbon stock, while also providing high value environmental, ecosystem and aesthetic co-benefits. According to the National Forest Inventory, 276,460 hectares in Ireland were under hedgerows in 2017 (DAFM, 2018a). Preliminary estimates by Black *et al.* (2014) indicated that hedgerows and non-forest woodland could potentially sequester 0.66 to 3.3 t CO_2 ha^{-1} yr^{-1} or provide a net removal of 0.27 to 1.4 Mt CO_2 yr^{-1}. However, there is limited research concerning management of hedgerows for optimum carbon sequestration. Research indicates that roughly half of hedgerows are appropriately maintained, with a considerable proportion exhibiting undesirable features such as gappiness or low basal density. Practices such as regular cutting, coppicing or hedge-laying will aid rejuvenation, while also enhancing many important co-benefits associated with hedgerows. Knowledge on hedgerows, along with associated best practice in management, needs to be consolidated, expanded on and shared with advisors and farmers. Existing CAP regulations recognises hedgerows as landscape features (under the Good Agricultural and Environmental Condition (GAEC) regulation 7). However, this provision does not ensure appropriate management and maintenance of hedgerows particularly in the context of carbon sequestration. GLAS includes hedge coppicing and laying actions, but the scheme is voluntary.

Mitigation Option 11. - Farm hedgerows

Incentives to encourage improved maintenance of existing hedgerows are required. It is recommended that field research is conducted to generate models on hedgerow biomass production and related carbon sequestration potential under different management scenarios. This would enable the development of a robust inventory system for hedgerows. However, effective means of gathering activity data needs consideration.

3.2.4 Carbon stocks in organic soils

Classified internationally as Histosols (FAO, 2015), organic soils include peatlands and organo-mineral soils (Wilson *et al.,* 2013) with the former exhibiting a peat layer > 30 cm depth that contains > 20% organic matter. If the peat layer is < 30 cm, the soil is considered organo-mineral (Duffy *et al.,* 2018; Renou-Wilson *et al.,* 2018). Peatlands account for roughly 3% of the global terrestrial area and are recognised as important sinks of carbon dioxide and sources of methane (Kroon *et al.,* 2010).

Organic soils under grassland

Wilson *et al.* 2013 estimated that between 300,000 and 375,000 hectares of peatland were under grassland in Ireland. Grasslands can be broadly classified into two categories, nutrient poor or nutrient rich (Renou-Wilson *et al.,* 2015). Agricultural production and associated drainage on nutrient poor sites should be encouraged to cease to enhance the carbon sink function. Rushes that are likely to encroach should be permitted under Cross Compliance regulations under these circumstances. Nutrient rich sites are considerable sources of greenhouse gasses (Renou-Wilson *et al.,* 2015; 2014). Theoretically the rewetting of such sites would be desirable, however, the economic sustainability and impacts at a wider catchment scale must be considered. The site-specific nature of restoration at multiple scales is emphasised. The Teagasc MACC analysis estimated that the cessation of drainage on 40,000 hectares would lead to emission avoidance of 0.44 Mt CO_2-eq yr^{-1} at a cost of €10.9 t CO_2-eq avoided. This was assumed to take place on extensive beef production systems (Lanigan *et al.,* 2018). Acquiring activity data on rewetting activity for inventory accounting needs to be developed. The drainage of some sites may have already ceased which requires identification.

Organic soils under forestry

Approximately 39% of forests in Ireland occur on former peatlands (DAFM, 2018a). The afforestation of relatively intact wetlands, causing a lowering of the water table and significant carbon losses, is not desirable. Despite afforestation of unenclosed or unimproved land being supported by afforestation grants, planting on unmodified raised bogs, industrial cutaway peatlands or infertile blanket or raised bogs is prohibited (DAFM, 2015). The impact on emissions of rewetting existing plantation sites following clear-felling, is unclear. At certain sites, rewetting may produce a net sink of carbon, while at others, re-planting may be beneficial. Additional research is required on management options and appropriate actions will be site specific.

Cutaway and cutover peatlands

Cutaway (industrial) and cutover (domestic) extracted peatlands are a major source of carbon dioxide. The rewetting of sites offers considerable mitigation potential. Rewetting of a cutaway blanket bog was found to reduce global warming potential by 87% and mitigate 75 t CO_2-eq ha^{-1} over six years (Wilson *et al.,* 2012). Research suggests rewetting may be highly cost efficient. Renou-Wilson & Wilson (2018) estimated an average cost effectiveness of €4 per t CO_2-eq avoided for rewetted industrial cutaway and cutover bogs. It is emphasised that the longer the rewetting process is delayed, the less likely peatlands will be able to sequester carbon. Additionally, climate change may further limit the carbon sequestration capacity potential.

There are multiple options for the after use of these lands including restoration, rewetting and paludiculture, or production on wet soils (Wichmann, 2017). It is important to identify on a case-by-case basis the appropriate after use to optimise environmental outcome and co-design the governance and incentives regime to realise environmental outcomes. Sites that have been drained but not subjected to peat extraction, and therefore retain original surface vegetation, should be prioritised for rewetting. Finally, it is important that the activity data which reflect management and the implementation of measures are captured at appropriate spatial and temporal scales. Innovation in mapping technologies may be useful in this regard.

Mitigation Option 12. - Organic soils

The management of organic soils provides a considerable opportunity for avoiding current carbon dioxide emissions and in certain cases, enable carbon sequestration.

Grasslands can be broadly classified into two categories, nutrient rich and nutrient poor. The potential for rewetting nutrient rich drained organic soils should be considered on a case-by-case basis. Where appropriate, rewetting should be implemented. For nutrient-poor organic soils under grassland, curtailing agricultural activity and allowing existing drains to deteriorate would enable natural reversion to a wetland habitat. It may be possible to incentives this through the habitat provisions under CAP Pillar 2. Means of gathering activity data would need to be developed.

Afforestation should continue to be not permitted on intact peatlands. Existing forest plantations on organic soils require careful management in order to optimise greenhouse gas mitigation and climate resilience of the landscape. Renewed efforts are required to cease all peat extraction and associated drainage of peatlands at industrial, semi-industrial and domestic scale. With consideration of catchment scale impacts, cutover and cutaway sites should be rewetted where appropriate.

3.3 AVOIDING CARBON DIOXIDE EMISSIONS THROUGH REDUCED FOSSIL FUEL USE

3.3.1 Reduction in on-farm energy consumption

Lanigan *et al.* (2018) identified a number of measures that could be implemented on dairy farms to reduce the consumption of energy and therefore avoid carbon dioxide emissions. These included plate coolers, solar panels, heat recovery systems and variable speed drives on vacuum pumps. Considering plausible sectoral uptake, these were considered cost negative at -€359 t CO_2-eq and projected to displace 0.029 Mt CO_2-eq per annum.

3.3.2 Energy from biomass

According to Lanigan *et al*. (2018), the use of thinnings, sawmill residues and wood waste for electricity and heat production could displace 0.759 Mt CO_2-eq annually at a cost of -€30.7 t CO_2-eq. The use of Short Rotation Coppice (SRC) willow and miscanthus for heat production was estimated to displace 0.179 Mt CO_2-eq per annum at a cost of -€20 t CO_2-eq. These values take account of the greenhouse gas footprint of willow and miscanthus production following the conversion of grassland (15,000 hectares) (Lanigan *et al.,* 2018). Finally, the use of willow for electricity production was estimated to displace 0.187 Mt CO_2-eq at a cost of -€10 t CO_2-eq displaced. This again assumed the conversion of grassland to willow plantations, with associated beef production continuing by higher stocking rates on alternative land. However, the production of miscanthus and willow to meet such demands is questionable in Ireland with bioenergy crops potentially deemed a less attractive option for farmers. Though dependent on future carbon prices, biomass may have greater value if utilised within the bioeconomy.

3.3.3 The bioeconomy and circular bioeconomy

With rapid global transition away from the use of fossil hydrocarbon resources, demand for land and marine resources to provide substitute raw materials will increase.

The bioeconomy refers collectively to all activities dependent on biological resources, systems and processes, from primary production to processing and refining, with emphasis on renewable inputs (EC, 2018d). It encompasses both terrestrial and marine ecosystems while linking multiple sectors that generate food, feed and bio-based energy, products and services. Ronzon & M'Barek (2018) estimated that the bioeconomy across Europe (EU-28) was worth €2.3 trillion and employed 22 million people in 2015. The enhancement of the bioeconomy is identified as means of driving sustainability (EC, 2012a; EC, 2012b) as outlined with the EU updated bioeconomy strategy (EC, 2018d). As the bioeconomy can engage with multiple sectors within the economy, it has potential to create jobs in rural and industrial areas, while also helping to ensure food security, reduce fossil fuel dependency, conserve or restore natural resources and aid climate change mitigation (EC, 2012a). Outputs of the bioeconomy not only include primary agricultural, forestry and marine products, but also bio-chemicals, bio-fuels, bio-based building materials, cosmetics or pharmaceuticals (EC, 2018d).

A circular economy describes a cyclical economic system, as opposed to the typical, linear model that involves the input of resources, their use and final disposal (Korhonen *et al.,* 2018). A circular economy involves the continual valorisation of one activity's waste as the input to another activity and applies at multiple levels, from individual companies, to a national scale, generating environmental, social and economic benefits (Kirchherr *et al.,* 2017).

A circular model of the bioeconomy presents alternative markets opportunities and activities to the agriculture and land use sector generating new income streams and enhance economic stability, therefore bringing social benefits, while also maintaining and enhancing the natural resources on which the sector is based. The circular approach helps drive the bioeconomy, ensuring the renewed and optimal use of resources and therefore the efficiency of the system, while avoiding fossil fuels. The bioeconomy is key to transforming wastes, discards and residues into valuable inputs. This may reduce the carbon footprint of products and ultimately reduces greenhouse gas emissions through carbon dioxide displacement, though is highly scenario dependant.

In Ireland, the bio and circular economies are increasingly recognised as a strategy in achieving decarbonisation, regional development, energy security from renewable sources, along with environmental protection, as outlined in the recent National Policy Statement on the Bioeconomy (Government of Ireland, 2018b). A number of bioeconomy projects have already been established, from research and development facilities such as the Beacon Bioeconomy SFI Research Centre (www.beaconcentre.ie), principally based at University College Dublin, to functioning enterprises. AgriChemWhey is a recently established, Glanbia-led industrial scale bio-refinery at Lisheen, Co. Tipperary (www.agrichemwhey.com). The plant aims to annually process 25,000 tonnes of whey permeate and de-lactosed whey permeate, both important side-streams of the dairy processing industry, into bio-based fertilisers, mineral supplements, lactic acid and poly-lactic acid. The latter materials can be used to make bio-plastics.

With regard to forestry, the substitution of energy intensive non-wood products, such as construction materials, with harvested wood products (HWP), can more effectively reduce greenhouse gas emissions compared to using wood as biomass for energy production (Geng *et al.,* 2017). The implementation of incentives for particular products could be beneficial, for example a reduced VAT rate on HWP. Research by Buchanan & Levine (1999) in New Zealand noted a 20% decreased in carbon emissions with a 17% increase in the substitution of building materials by durable plywood products. This represented a 1.5% reduction in New Zealand's national emission at the time (Buchanan

& Levine, 1999). Harte (2017) highlighted the increasing use of engineered wood products known as mass timber. Cross-laminated timber (CLT) has high load carrying capacity facilitating high-rise construction. CLT is suggested to increasingly provide an economically viable and sustainable alternative to traditional construction materials. However, both research and use of HWP in construction in Ireland appears limited. None the less, CLT has been used in a number of Irish construction projects (Harte, 2017).

It is worth noting that existing carbon accounting mechanisms may not fully account for potential carbon sequestration within long-lived HWP such as construction materials. Geng *et al*. (2017) concluded that depending on the end-use, HWP retain carbon and represent an important aspect of forest carbon cycles and balances. There is considerable opportunity for increased HWP use, which provides long-term and stable carbon storage while also providing potential mitigation (avoided emissions) due to substitution of HWP from fossil fuels intensive products, including plastics and concrete. Duffy *et al.* (2019) estimated removals from HWP of - 871.6 kt CO_2-eq in 2017.

Considering anaerobic digestion, Lanigan *et al.* (2018) examined the utilisation of grass in conjunction with slurry for heat and energy production as well as gas that can be injected into the national grid. Estimated mean annual displacement of 0.224 Mt CO_2-eq at a cost of €115 t CO_2-eq was estimated. The anaerobic digestion of grass and slurry and further refinement to produce methane gas for use within the national gas grid was estimated to displace 0.15 Mt CO_2-eq yr^{-1} at a cost of €280 t CO_2-eq, and therefore expensive. Where carbon dioxide emissions are displaced, other greenhouse gases may be emitted. For example, grass is utilised to fuel anaerobic digestion, but may be dependent on high nitrogen fertiliser inputs, the production of which generates significant greenhouse gas emissions, therefore offsetting some benefits of the carbon dioxide avoided. Powlson *et al.* (2011) highlighted this with regard to carbon sequestration with increased crop growth production that is reliant on high fertiliser inputs. However, the establishment of clover within grass swards will reduce some, or all of the need for fertilisers. The Teagasc MACC analysis considered emissions associated with fertilisers with regard to national inventory accounting (Lanigan *et al.,* 2018). Emissions from the production of fertilisers were therefore omitted, as this takes place outside Ireland. The utilisation of grass for anaerobic digestion, may also offset potential methane emissions if that grass was to be used for ruminant production.

There is considerable opportunity for agriculture and forestry to drive the bioeconomy while, following a circular approach, receiving the outputs from processes higher up the value-chain to use as inputs for agricultural and forestry activity, therefore displacing the need for fossil fuel dependant inputs. Emphasis is placed on closed-loop systems (Toop *et al.,* 2018), even at farm level, where one enterprise' output is an input to another with a shift away from current agriculture model, which is resource intensive (Ward *et al.,* 2018). There is particular emphasis on soil restoration and its optimisation as a carbon sink (EC, 2018a) as well as eliminating waste at all stages of the production process. The circular approach in agriculture consolidates and incorporates a lot of the mitigation and sequestration measures previously discussed, while additionally contributing significantly to carbon dioxide displacement.

Mitigation Option 13. – Bioeconomy and Circular Bioeconomy

Further scoping, research and development is required to enable the agriculture and land use sector to engage with and foster a robust circular bioeconomy, at local, regional and national levels. This will require identification and quantification of potential primary products, including wastes, discards and residues, appropriate markets or value-chains for these products and the development of the required technology for their utilization. The production of biomass for energy production may be feasible in the short-term, however biomass may have greater economic and carbon dioxide displacement value, within the context of the bioeconomy in the long-term.

3.4 Enabling Greenhouse Gas Mitigation

3.4.1 Changes to the Common Agricultural Policy

Proposed changes to CAP include greater emphasis on climate change action, with focus on limiting carbon losses from wetlands and peatlands as well as improved nutrient management to reduce nitrous oxide emissions. Simplification of the policy and more performance or result-based support is emphasised. Nine common objectives will be included, of which three will relate to environmental management. These are environmental care, landscape and biodiversity preservation, and action on climate change. It is proposed that 30% of Pillar II funds will be spent on measures including climate action, with 40% of the overall CAP budget expected to be spent on climate mitigation (Callanan, 2018). Additionally, the European Commission recognises the local and regional nature of environmental and climate issues and the potential of tailored design of schemes for effective support of actions and measures.

Anecdotal evidence suggests that farmers may be willing to extensify production and engage in environmental conservation, which may include greenhouse gas mitigation measures, but are constrained by maximising output to make sufficient returns. Past and existing environmental incentives and supports are suggested to have been, or to be, short-lived, inconsistent or insufficient. In short, there appears to be an appetite to enhance the environmental sustainability of the sector among the farming community, however, anecdotally there is a lack of direction and long-term, consistent supports for environmental conservation measures, which may present barriers to changes in management.

The proposed changes to CAP present a considerable opportunity to enable climate change mitigation. It is vital that changes provide sufficient, consistent and long-term support for environmental conservation and specifically implementation of greenhouse gas mitigation measures.

Enabling Mitigation 1. – Changes to the Common Agricultural Policy

Changes to the CAP include increased control and design by EU Member States in conjunction with a greater emphasis on environmental measures, including climate change mitigation. This presents an important opportunity to enable the implementation of mitigation measures within the Irish agricultural sector and should be fully utilised to do so.

3.4.2 National Land Use Strategy

How Ireland would benefit from a land use strategy?

In Ireland, current land use planning pertains primarily to residential and urban development (OECD, 2017) but there is limited attention to land more generally and in particular, the role of land in the delivery of functions beyond production. Land and ultimately soil, is a vital and finite resource delivering multiple functions and ecosystem services on which all life is based (Hillel, 1991; Haygarth & Ritz, 2009; Oliver & Gregory, 2015). These functions and services include atmospheric or climatic regulation (FAO & ITPS, 2015) and therefore potentially, climate change mitigation. Land management should accommodate and aim to enhance multiple land functions, (Haygarth & Ritz, 2009; O'Sullivan *et al.,* 2015; CCC, 2018), while simultaneously enhancing land-based incomes and rendering the sector less vulnerable to market volatility. However, there may be trade-offs or synergies in delivering multiple land functions (Schulte *et al.,* 2014; Schulte *et al.,* 2015). Management that prioritises one function, often productivity, may impact the delivery of other functions (Schulte *et al.,* 2015; Coyle e*t al*., 2016). The productive function, just one of many land functions and perhaps the most widely recognised, refers to the provision of food, feed, fuel and fibre (Mueller *et al.,* 2013) by means of agricultural and forestry systems. It is recognised that the global intensification of agriculture has been at the expense of other land functions, particularly biodiversity provision (Foley, 2005; Van Vooren *et al*., 2017). Agriculture occupies a considerable portion of the global land area (Ramankutty *et al.,* 2008) as is the case in Ireland (EPA, 2016), putting pressure on the capacity of land to support other functions and ecosystem services. However, agricultural production may co-exist with the successful delivery of other functions. For example, extensive farming systems (Benayas & Bullock, 2012) may facilitate aesthetic landscape features (Assandri *et al.,* 2018), while the integration of features such as hedgerows or grass strips (Van Vooren *et al.,* 2017) into arable systems, may support biodiversity. The potential for agricultural production to co-exist with enhanced biodiversity is demonstrated by HNV farmland (Stohback *et al.,* 2015; EPA, 2016). An alternative approach is the separation or compartmentalisation of land by function and associated intensification of functions within sections of landscapes (Benayas & Bullock, 2012; Balmford *et al.,* 2018). Both approaches have merits and limitations and may be appropriate in different scenarios. However, intensification of production within certain areas, is likely to limit the range of ecosystem services provided, on which that agricultural production depends.

It must be noted that there are climatic and geo-physical limitations to land functions, as not all land can support all functions to the same capacity (Schulte *et al.,* 2015). Beyond natural limitations, the degree to which land can optimally support functions is dictated by management. For example, different soil types support certain functions better (Schulte *et al.,* 2015; Coyle *et al.,* 2016), which can be realised or prevented through management. In addition, different land functions require management at different scales. For example, water quality must be managed at all scales, while production of food and fibre, is managed at field and farm scale. To ensure the optimal, balanced and appropriate delivery of multiple land functions and ecosystems services, including greenhouse gas mitigation, in conjunction with satisfying diverse policy requirements, the management of land at farm, catchment and national scales is arguably vital. Additionally, the likely impacts of climate change mitigation measures should be considered within a landscape context (Bourke *et al.,* 2014).

Given the important contribution of LULUCF and following the National Planning Framework (Government of Ireland, 2018a), a strategic approach to land use in Ireland, considering multiple scales and notably, climate change mitigation, may be useful to determine the most appropriate land use options and direct policy and incentives accordingly. More specifically, a national land use strategy could (i) facilitate an assessment of land resources and current management, (ii) determine most holistically sustainable uses of land by testing optimisation scenarios at multiple spatial scales and (iii) guide policy, including aspects of the Common Agricultural Policy, to encourage and achieve desired management. Therefore, a land use strategy approach should not be prescriptive, but act as a decision support tool to guide actions for desired outcomes.

This was previously recommended by the Climate Change Advisory Council (CCAC, 2017; 2018) while the necessity of a collective land management policy specifically concerning greenhouse gas emissions has been emphasised elsewhere (Schulze *et al.,* 2009) including the UK (CCC, 2018). There is also recognition of the need for an integrated land systems approach at a European level to manage land uses and combat processes that limit land functions, including soil degradation (EEA, 2018). The coordination of European policy instruments is identified as an important next step (EASAC, 2017).

A land use strategy in Ireland could incorporate all relevant and evolving environmental legislation such as the Nitrates Directive, Habitats Directive, Air Quality Standards Regulations, National Emissions Ceilings Directive, and National Energy and Climate

Policy. The generation of renewable energy via wind, solar PV or biomass on agricultural land is one opportunity to contribute directly and indirectly to environmental legislation (ISEA, 2014). A land use strategy could also incorporate un-legislated topics of concern such as soil quality conservation. While Irish soils are of relatively high quality (Kiely *et al.,* 2014), it is imperative that this status is maintained.

Finally, a land-use strategy can incorporate relevant stakeholder opinions and knowledge, aiding a just transition, while providing a system for monitoring progress and acting on feedback. It is crucial that the integrated impacts of multiple mitigation measures at farm, catchment and national scales are measured and monitored.

Enhanced ecosystem services delivery as a framework for a land use strategy

A land use strategy could focus on climate change mitigation but would be limited if other ecosystem services and their sustainable delivery were not considered. Therefore, the pursuit of enhancing and facilitating the delivery of multiple ecosystem services could form an appropriate framework for a land use strategy, thereby ensuring mitigation measures are sustainable, bringing multiple co-benefits and aiding long-term environmental conservation. Aspects such as flooding or erosion prevention, nutrient cycling, pollinator conservation and enhanced landscape aesthetics as a basis for recreation and cultural traditions (Costanza *et al.,* 1997; Guerry *et al.,* 2015) should be pursued in conjunction with greenhouse gas mitigation. The pursuit of optimised multiple ecosystem service delivery could therefore also contribute to resiliency and climate change adaptation, while providing a range of co-benefits to society. A research project, funded by the EPA, is about to commence that will conduct ecosystem accounting of a catchment, considering components such as aquatic systems, wetlands, forestry, farming, industry and settlement. This may provide useful insight into how to develop and guide land use aspects of a land use strategy to enhance ecosystem service delivery.

What a national land use strategy could look like

The optimal delivery of multiple ecosystems services is underpinned by maintaining and enhancing diversity, notably biodiversity within the landscape. Diversity is required at genetic, species and habitat scales to ensure resilience to sudden environmental stresses at multiple scales. In this context, mitigation measures such as multi-species swards, hedgerows or agroforestry clearly enhance ecosystem service delivery potential at a field or farm scale. At a landscape scale, diversity should be encouraged through the conservation of wetlands, mixed species woodlands and other natural and semi-natural habitats. The importance of diversity within afforestation is highlighted (Seddon *et al.,* 2019). While dairy production is economically rewarding at present (Dillon *et al.,* 2018), increased specialisation and the dominance of typically, intensively managed dairy systems within a landscape may be undesirable in the long-term, not only in terms of ecosystem service delivery but also food production capacity and resilience to external shocks, including markets.

The UK Committee on Climate Change (CCC, 2018) highlighted the need for releasing agricultural land for alternative uses such as afforestation, peatland restoration and water catchment management. Diversification within the agriculture sector was also identified as important. Economic supports to farmers for alternative land function provision along with “downstream” factors such as consumer behaviour regarding diets and food waste, were identified as facilitating land use change.

The technical mechanism for achieving a national land use strategy requires research and expert consultation. A number of studies may provide useful insights.

Hochstrasser & Herzig (2018) applied the Land Use Management Support System (LUMASS) model in Ireland on the Suir catchment, showing its potential use. This software platform can support decision making, including initial assessment and design. LUMASS combines spatial data from multiple inventories to identify optimal land use at catchment scales for desired outcomes (Herzig & Rutledge, 2013). The study highlighted the opportunity for stakeholder engagement at each stage of the model’s development, from selecting optimisation criteria, designing scenarios, to the assessment of optimal land utilization. However, the model’s value is dependent on the quality and availability of data and it was suggested that high-resolution spatial datasets are required to capture all ecosystem services.

Functional Land Management described by Schulte *et al.* (2015) aims to provide a framework for policy design to ensure balanced delivery of different land or soil functions. This has emphasis on soil management and recognises the different spatial scales required to optimally deliver different land functions.

The EPA-funded Environmental Sensitivity Mapping (ESM) project has developed an interactive map that indicates spatial environmental sensitivities, incorporating GIS data layers and is designed specifically to aid planning and support in Strategic Environmental Assessments (González Del Campo *et al.,* 2019). This system should be publicly available in Autumn 2019 and may provide a valuable tool for developing a land use strategy.

The mapping of implemented mitigation measures and monitoring of data at a localised or catchment scale, such as the rewetting of peatlands (Renou-Wilson *et al.,* 2018), is also vital. Hochstrasser & Herzing (2018) emphasised the importance of feedback and an adaptive learning process. Major changes in land management may lead to greater problems. Careful selection of indicators that measure the holistic impacts of changes in land use is critical for effective monitoring.

Enabling Mitigation 2. - A national land use strategy

A national land use strategy could help enable the balanced and sustainable provision of multiple land functions and ecosystem services at both a landscape and national level, including greenhouse gas mitigation. A land use strategy could focus on climate change mitigation, but within a framework of pursuing enhanced delivery of multiple ecosystem services, thereby ensuring mitigation measures also facilitate long-term environmental conservation, provide multiple co-benefits to society, while contributing to resiliency and climate change adaptation. The strategy could help encourage the delivery of optimal land uses, considering environmental, social and economic aspects, by guiding policy and supports to incentivise desirable land management. Therefore, the strategy would not be prescriptive but form a decision support tool. Additional research and development is required to elaborate further on potential policy design and implementation measures to enable appropriate land use and land management decisions across all sectors.

3.4.3 Improved knowledge exchange

The success of AFOLU mitigation policy is largely dependent on farmers' and other land managers' perceptions, lived experiences and understanding of climate change. Equally, the active participation and incorporation of land mangers' knowledge, opinions and experience is critical in the design of sustainable mitigation measures and associated policy.

There is limited research available which has sought to explore farmers' attitudes to and awareness of climate change issues in Ireland. A survey conducted in 2014 explored farmers' awareness of and willingness to act on climate change as part of assessing potential use of an information technology (IT) tool to aid greenhouse gas mitigation (Tzemi & Breen, 2018). The study acknowledges some limitations but is indicative of the situation at that time. Approximately 53% of the farmers surveyed (n = 746) felt that anthropogenic activity was contributing to climate change. However, 27.5% believed that the consequences of climate change will only be relevant in the long-term, while 28.9% considered that there will be no consequences at all. Interestingly, arable (tillage) farmers were found to have the most optimistic outlook about impacts, which may relate to expectations of higher yields as a result of warming temperature. Approximately 30% of farmers disagreed that livestock production was a source of emissions, though 69% considered deforestation to be a key contributor. It was suggested that the global media emphasis on the negative impacts of deforestation had influenced perceptions, with potentially less awareness of Ireland's emissions profile (Tzemi & Breen, 2018).

Since the survey by Tzemi & Breen was conducted, the frequency of extreme weather events has increased (Met Éireann, no date), and likely to have influenced farmers' lived experience of climate change. In addition, there has been increased media focus on the contribution of the agriculture sector on Ireland's national emissions profile. Research is required to explore how land managers' and farmers' perceptions may have changed. Effective advisory services and courses within educational institutions are vital in addressing potential knowledge deficits.

As mentioned, farmers appear keen to engage in environmental conservation measures, including those relating to greenhouse gas mitigation (Section 3.4.1). Anecdotal evidence indicates an awareness among farming communities of changing weather patterns, notably precipitation intensity and frequency that has necessitated adjusted farm management. This may signify a shift in awareness and opinions of farmers in recent years. Anecdotal evidence also suggests that proposed climate change mitigation policy may be prescriptive and implemented in a top down manner. This indicates that farmers' knowledge and experience has been largely omitted, with little active participation from farming communities in the design of mitigation measures and actions to respond to climate change. One-way transfer of knowledge undermines the future success of climate mitigation policy, in that it inherently implies that farmers' and land managers' experience and knowledge of the land is not valued. In practice, indigenous knowledge of land at a localised or field scale can be valuable in informing science and best practice. Additionally, local knowledge regarding social and cultural values within communities can help to inform the communication of scientific evidence, and in turn inform the design of policy.

Knowledge exchange between farmers, rural communities and policy makers is critical to enabling the development and implementation of holistic and sustainable policy responses, that can address the wider social and environmental impacts of climate change on rural Ireland.

Afforestation faces considerable social and behavioural barriers, some irrespective of economics (Farelly & Gallagher, 2015; Ryan & O'Donoghue, 2016; Ryan *et al.,* 2018). Issues associated with the required re-classification of agricultural land have been briefly mentioned (Section 3.2.2). Ryan and O'Donoghue (2016) found that 84% of farmers surveyed would not consider afforestation while more recent work suggested that some younger farmers on larger farms, may be willing to consider afforestation, if financial returns are greater than those obtained from agriculture (Ryan *et al.,* 2018). The research also highlighted a reluctance of some older farmers on smaller holdings to consider afforestation, regardless of economic incentives. Current afforestation grants and premia are outlined in Appendix 2 (Section A.2.2).

Finally it is suggested that farmers are receiving mixed messages regarding management decisions. The market currently provides the clearest signal, which encourages production expansion, with climate change mitigation an emerging lesser factor. This in-coherence of messages in conjunction with a potential knowledge deficit on specific mitigation measures, may exacerbate any barriers to adoption and temper the potential willingness for action. In addition to financial support to enable mitigation, the provision of information and direction is now required to facilitate management changes.

Enabling Mitigation 3. - Improved knowledge exchange

A study conducted in 2014 indicated that a lack of awareness regarding climate change existed among farmers. The adoption of mitigation measures is dependent on knowledge of both, reasons behind and direct measure implementation. Research is required to explore how farmers' and other land managers' perceptions may have changed in recent years. The role of agricultural advisory services, media and educational institutions is crucial where knowledge deficits exist. Equally, it appears there has been limited opportunity for active participation from farmers and other land managers within the policy design process. Their knowledge, opinions and lived experience is crucial in the design of acceptable, holistic mitigation strategies while addressing wider social and environmental issues in rural Ireland. Research and resources to enable effective knowledge exchange is required.

3.4.4 Agriculture and just transition

Mitigation options within the AFOLU sector have been discussed. This section explores the underlying interconnected challenges to implementing mitigation options in the context of a just transition, which requires greater consideration of the social and environmental impacts in the development of responses to climate change.

Ireland's agriculture and agri-food sector has the potential to be a leader in climate action by demonstrating how to transform food production in the face of climate change and addressing environmental degradation, both locally and globally. This will require greater collaboration between policy makers, farmers and rural communities to develop solutions that add to Ireland's food security while supporting a low carbon future that prioritises environmental and human health (WHO, 2018). However, collaboration will require the focus of policy in the agricultural sector to be broadened beyond the scope of economics alone. This will involve considering how agriculture policy aligns with for example, environmental policy, national health policy and social policy as well as overseas development policy. Understanding the synergies between these policy areas may present a novel means of addressing the challenges facing agriculture in a low carbon future and enable a just transition.

To identify how the opportunities may be realised an understanding of what constitutes a just transition is required, along with an understanding of the barriers and challenges in the sector.

Just Transition

Increasingly there is a call, in society and in academic literature, for a movement towards a just transition (Bulkeley *et. al.*, 2014; Whyte, 2018). This is not a move away from climate justice, but, an enhancement of the framework for understanding how the transition to a low-carbon society needs to be equitable and cause no harm. Climate justice is one of three forms of justice that need to be considered in a just transition to a low carbon future (Figure 8), with energy and environmental justice forming additional key components (McCauley & Heffron, 2018).

Climate justice links human rights and development to achieve a human-centred approach, safeguarding the rights of the most vulnerable and sharing the burdens and benefits of climate change and its resolution equitably and fairly. Climate justice is informed by science, responds to science and acknowledges the need for equitable stewardship of the world's resources (MRCJ, 2013).

Energy justice applies human rights across the energy life cycle. The focus is on insuring that people have access to energy to maintain a decent quality of life, while guaranteeing the production and distribution of energy is done in a manner that causes no harm (Jenkins *et al.,* 2016).

Environmental justice is concerned with the inclusion of citizens in the development, implementation and enforcement of laws, regulations and policies regarding the environment; central to this is equity. It is important to note that justice is considered not merely as an outcome of policy, but within the policy process itself (Jenkins *et al.,* 2016; Whyte, 2018).

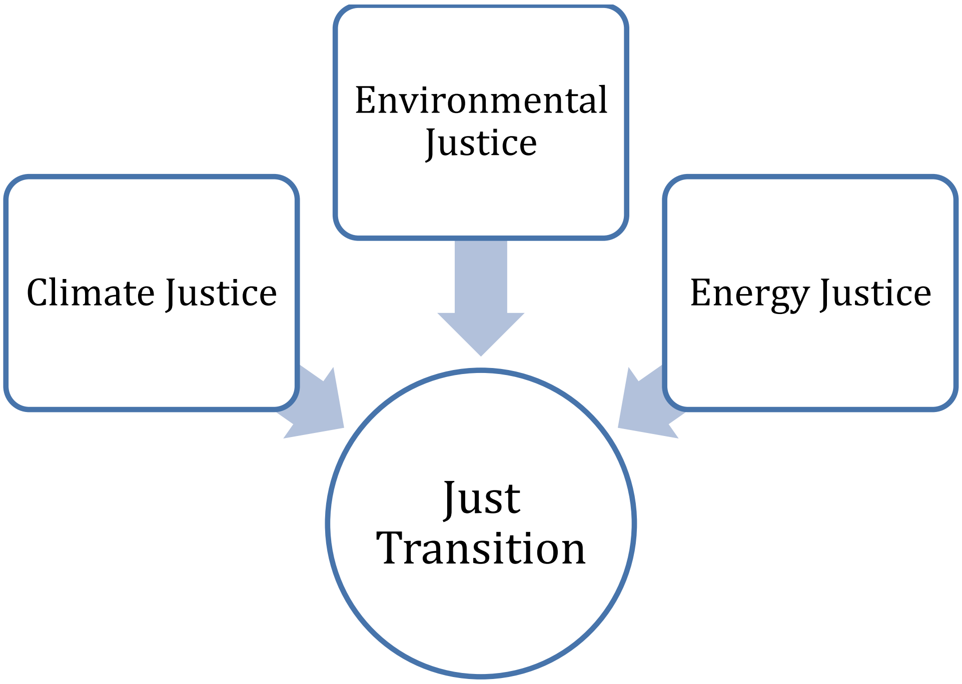


Figure 8 Components of the Just Transition

In addition to these three justices, is the concept of restorative justice (Heffron & McCauley, 2018; Whyte, 2018). This refers to the recognition and acceptance of past grievances and mistakes in order to progress and collaboratively develop solutions. Consent and reconciliation are needed to have an equitable distribution of the burdens and opportunities of responding to climate change (Bulkeley *et al.,* 2014; Heffron & McCauley, 2018; Whyte, 2018). A dialogue that is respectful, deliberate and considerate, and aimed at understanding the barriers and challenges faced by at-risk individuals and communities is valuable to the longevity of climate action (Bulkeley *et al.,* 2014; Dekker, 2018; Heffron & McCauley, 2018; Whyte, 2018). Imposing solutions may do more harm to these individuals and communities and increases the risk of U-turns on policies that are essential for mitigation and adaptation. The policy development process should consider underlying causes of individuals' and communities' increased risk and vulnerability to climate change as well as the impacts of proposed mitigation or adaptation measures.

A just transition moves beyond protecting the rights of vulnerable individuals, to understanding the causes of vulnerability and how responding to climate change is an opportunity to engage in restorative justice (McCauley & Heffron, 2018). It is necessary to actively engage with vulnerable and underrepresented groups considering gender, ethnicity and socio-economic status in developing responses to climate change.

There are two dimensions to the Just Transition in the Irish context: (i) achieving a just transition in the domestic sphere; and (ii) contributing to a just transition internationally. Achieving a just transition is not without challenges locally and internationally. Ireland has the potential to be a leader and to show how a nation can transition from relatively carbon intensive food production and land management to an equitable low-carbon society by designing and implementing policy that leaves no one behind.

A just transition calls for understanding the root causes of problems, and how individuals and communities want to address their challenges (Heffron & McCauley, 2018; Whyte, 2018). At the core of this, is fostering a culture of respect and dignity. Respectful and open dialogue about individuals and communities 'hopes and concerns' is imperative. Table 8 presents a process of engagement to develop responses to climate change that achieve resilience. Collaboration with stakeholders who recognise the existence of a threat and are ready to take action is crucial.

Table 8 Resilience process - complex system (Source: Dekker, 2018)

Pre- Conditions	Recognition of a threat Perceptions of: • Vulnerability created by threat • Risks stemming from threat Knowledge of: • Threat • Causal pathways • Mechanisms Desire to take action
Agreement of Threat	Action to become resilient
Resilience Process	Analysis of Threats:

	• Risks • Assessment of impacts • Knowledge exchange (i.e. information about threat outcomes) • Collaboration/ Collective action • Integrated action Debate on Action: • Assessment of possible actions • Assessment of risk associated with actions • Role clarification (stakeholders and their agendas) • Options: short and long run Visioning of state of being resilient Implementation Monitoring and evaluation • Resilience achieved as an endpoint or an on-going process

Engaging in this process within the Irish agricultural sector will be challenging, as the dialogue around climate change and agricultural policy can be politically difficult. Anecdotal evidence indicates that wider dialogue and policies have not fully considered the importance of the social and cultural aspects of agriculture.

There is an alienation of farmers, whereby they are perceived to be the cause of the problem, as opposed to being part of the solution as a key contributor with their knowledge and expertise. Agriculture is at the core of rural communities and identity across Ireland, it is more than the production of food.

In terms of changes in policy and in order to climate-proof policy in Ireland, it is important to consider current events but with recognition of the historical context of agriculture. Additionally, the social and cultural values placed on the land must be considered. Anecdotal evidence also suggests that the sector is viewed as an unattractive or unviable profession, especially with respect to future generations, as in other countries (Sulemana & James, 2014; Zou *et al*, 2018). This needs to be researched in the Irish context. Farming is a challenging livelihood, where income can be relatively low (Dillon *et al.,* 2018), work is labour intensive and potentially conducted in isolation. External challenges to the system, including market shocks, social isolation and climate related impacts such as flooding and drought, pose a significant risk to health and well-being (Sulemana & James, 2014; Campbell *et al,* 2018; WHO, 2018; Zou *et al.,* 2018). Finally, agriculture and its role in public health, regarding the production of wholesome food and the provision of public goods including landscape aesthetics, associated cultural values and habitats for biodiversity, need consideration.

Agriculture, food security and climate change: a global and local public health problem

The publication of the IPCC's 1.5 Degree Report (IPCC, 2018) and the EAT Lancet Commission Report (Willett *et. al.*, 2019) has drawn attention to food production and consumption. The reports have called for a global shift towards eating less meat. They also highlight the challenges inherent in the global food system, which in its current state, is carbon and water intensive. The COP24 Special Report: Health and Climate Change (WHO, 2018) also highlights the challenges ahead, while acknowledging that there are inherent opportunities in addressing the agriculture and food sector with balanced supply side and demand side actions. Critically, the World Health Organisation has highlighted the key reason for climate action, and one in which agriculture is central - human health:

> '"Climate action is development action"; as social resilience and economic productivity depend on the good health of populations, health must be central to climate change policy' (WHO, 2018).

The decarbonisation of agriculture is a global challenge, one that is complicated by climate change and urbanisation (Campbell *et al.*, 2018; WHO, 2018). At present, 50% of the world's population live in cities, this is projected to increase to 70% by 2050 (UN Habitat, 2016). Urbanisation is being driven by factors such as education and employment opportunities in urban areas. With urbanisation, comes the challenge of feeding urban populations, as well as providing affordable housing and transport options. On the surface, access to food, housing and transport appear to be separate policy issues however, they are interdependent. Research in public health policy highlights the importance of the Social Determinants of Health (SDHs) in health outcomes (Galvão *et al.,* 2009; Barton, 2009). The SDHs are mentioned here to highlight the importance of health to economic productivity, both in rural and urban areas. Incomes are a determinant of health, as individuals and families will choose to prioritise their spending based on their needs depending on, and relative to their income security. This may result in individuals and families forgoing wholesome food for processed food due to the costs of housing and transport placing a greater demand on their income (Galvão *et al.,* 2009; Barton, 2009; Dekker, 2014a; 2014b).

Growing urban populations are increasingly dependent on a declining number of farmers to provide food that is both healthy and affordable (UN Habitat 2016; WHO, 2018; Zou *et. al.,* 2018). There are new and growing nutritional challenges such as obesity, malnutrition and food wastelands stemming from access to affordable healthy food within urban contexts (Campbell *et al.,* 2018; WHO, 2018). These challenges are connected to the distribution of food, which highlights the vulnerability of human health to changes in food availability and supply chains (Campbell *et al.,* 2018; WHO, 2018). While Ireland's foreign policy acknowledges that the distribution of food globally is unequal, and that under-nutrition is the main contributor to childhood death, food distribution and affordability is not considered in the national context (Godfray *et. al.,* 2010).

There is an opportunity to demonstrate leadership on climate proofing agriculture and food policy. However, in Ireland, there are challenges that have not featured strongly in national discussions around climate change and agriculture. These include population health, national food security, water supply and security, and impacts on international trade. As an open market economy, Ireland is not food independent and climate change has the potential to disrupt food supply chains. In 2018, Storms Emma and the "Beast from the East" demonstrated Ireland's dependence on imports for food and the vulnerability of the water supply system. The drought during summer 2018 further illustrated Ireland's water insecurity and its impact on the ability of farmers to sustain production levels and guarantee their incomes. Climate change will impact the health status of people in Ireland (WHO, 2018).

The "Healthy Ireland – A Framework for Improved Health and Wellbeing 2013-2025" Report, notes emerging concerns regarding malnutrition, specifically obesity, which is primarily linked to diabetes but can mask other nutrient deficiencies and malnutrition (DOH, 2012). Solutions to these challenges may include promoting active lifestyles, community gardens, urban agriculture and social farming. Less discussed, though is our dependence on a decreasing number of farmers to deliver nutritious and affordable food, and the costs added along the food supply chain to bring food to people. Policy responses should be holistic to achieve resilience in the agriculture and food systems locally and globally in a just manner. If people are to be healthy, they need to be able to afford food that is wholesome.

Responding to the increased demand for food will need a diverse and resilient range of policy solutions that include (Godfray *et al.,* 2010): extensification, diversification, social farming, urban agriculture and spatial planning that considers alternative land-uses, infrastructure (energy, water and telecommunications) and transportation connectivity. Development and implementation of policy solutions will need active engagement, which will be challenging, but necessary.

Challenges and opportunities

It will be critical to understand how policies at the EU and international level have changed and shaped the Agriculture and Agri-food Sector in Ireland. The Common Agricultural Policy sought to guarantee fair prices to producers (farmers) and provide affordable food across Europe. This generated change within Ireland's agricultural practices, from mixed to specialised systems. To change policy, consideration of the sector's history and the socio-cultural values associated with the land is needed.

Farming provides a strong social identity for those involved. Farm holdings may have been in families for generations, with a sense of connection felt by the individual and families concerned, to the land. Farming is about more than an income. Such social aspects may not be properly considered in policy, which currently tends to focus on short-term quantifiable economic impacts (McCauley & Heffron, 2018). The long-term social, environmental and economic impacts are harder to quantify and therefore are absent.

Translating the loss of social connection and the mental health impacts of losing one's job into economic terms is currently not considered within policy making processes. The World Health Organisation has acknowledged that depression is the leading cause of absenteeism from work (WHO, 2017). Causes of depression are broad, as are the impacts of depression. It affects not just an individual but their entire family, community and society. Using a just transition framework to design policy will allow consideration of social impacts of policy (McCauley & Heffron, 2018).

Policy regarding the transition of the fossil fuel sector in Alberta, Canada, provides an example, where the health and well-being of workers was a priority (Marshall *et. al.,* 2018). Policy makers engaged with workers from the outset to understand their vision, hopes and concerns about the future and their role in it. Backlash was minimal from workers as they acknowledged that the future of energy was not coal, but renewables. Having the opportunity to contribute to the design of policy that would affect their livelihoods, rather than having a policy imposed upon them, enabled the government to make progress on the transition out of coal. Ireland could similarly demonstrate leadership by working with the agriculture and agri-food sector to make it more resilient while still supplying food locally and globally.

Achieving a just transition requires an all of government plan

Acknowledging that a just transition is concerned about doing no harm it is worth highlighting Article 25 of the UN Declaration on Human Rights before discussing actions for a just transition.

> "Everyone has the right to a standard of living adequate for the health and well-being of himself [herself] and of his [her] family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his [her] control" - Article 25(1) of the UN Declaration of Human Rights

Policy actions and measures to mitigate the impacts of climate change on the agriculture sector need to consider the broader context. Climate action is not just about reducing emissions. It is about society, understanding, how this affects us all and how we are going address this problem that has been created by us (Dekker, 2018; Heffron & McCauley, 2018; McCauley & Heffron, 2018; Whyte, 2018).

Ireland can demonstrate leadership by working with the agriculture and agri-food sector to make it more resilient while still supplying food locally and globally. For example, the Smart Farming programme, developed by the Irish Farmer's Association with funding from the EPA and support from Teagasc, aims to inform farmers on ways to protect the environment while saving on costs associated with energy, fertiliser and water use.

All farmers in Ireland need to be effectively represented in policy development that impacts on their livelihoods. As mentioned, families have farmed for generations and have an intimate knowledge of their land. Farmers understand the consequences of legislation and regulations and how these translate at farm level. They know what is needed to progress. The transition to low carbon agriculture and a food secure Ireland is a process. It will take time and dialogue, during which conflict will arise but will serve as an opportunity to learn and inform policy-making.

The Irish Government has the policy tools and resources to enable a just transition. One is the Citizens' Assembly, which has been recognised internationally as an ideal model of public participation in national government policy development. Though not necessarily dealing with climate change, the agricultural European Innovation Partnership (EIP-AGRI) aims to facilitate and support the engagement of farmers and land managers with other stakeholders in designing localised solutions to environmental issues (EC, no date; DAFM, 2019). Greater emphasis could be placed on greenhouse gas mitigation in conjunction with addressing other environmental concerns. Opportunities also exist to work with the National Dialogue on Climate Action to explain the national transition, explore opportunities for the sector and contribute to the further development of policy.

As local authorities across the country develop their climate action plans with the support of Climate Action Regional Offices, there is an opportunity for active and continuous public participation that supports the agricultural sector and achieves social and economic growth in rural Ireland. At present, Fingal and South Dublin County Councils, have indicated that they will support farmers with GLAS measures in their Climate Action Plans. Local authorities need not limit their action to GLAS and should consider the potential of urban agriculture and social farming. Social Farming has been active in County Kerry for a number of years (www.kerrysocialfarming.ie) and has been successful in providing social supports for individuals with disabilities. The programme could serve as a template for social farming across the country. Both social farming and urban agriculture can contribute to climate change mitigation, adaptation and provide social benefits for citizens by fostering a connection with nature, an understanding of food production and promoting constructive dialogue.

In summary, the Irish Government has the capacity to achieve a just transition within the agriculture sector and can be a global leader in the field. This will require greater collaboration with farmers and communities in the policy making process in order to capture their valuable knowledge and lived experience. This will take an investment of time and dialogue, that will pay dividends going forward. The active engagement process employed by the Citizens' Assembly provides an example of how to collaborate and incorporate a diverse range of views in a meaningful way and will enable a just transition.

Enabling Mitigation 4. – just transition in agriculture

The need for just transition in responding to climate change is highlighted internationally. The Just Transition provides a framework for understanding how the transition to a low-carbon society is to be equitable and minimise the negative impacts for all stakeholders, notably farmers and rural communities. The development of climate related policy should consider underlying causes of individuals' and communities' increased risk and vulnerability to not only the impact of climate but, of proposed mitigation measures. Participatory approaches for engagement are fundamental to this. Approaches adopted by the Citizens' Assembly and under the European Innovation Partnership (EIP) programme may be useful in facilitating engagement and ultimately strong stakeholder ownership of mitigation policies and therefore help achieve just transition.

Table 9. Summary and classification of mitigation measures with regard to perceived attributes (Reducing Agricultural Emissions)

Measure	Predicted Annual Effectiveness	Ease of Inventory Capture	Estimated Annual Cost	Ease of Deployment (Opportunity Costs)	Overall Rating
Gradual Reduction in Bovine Numbers	Requires Research	Easy (Bovine number reductions and associated direct and indirect (manure) emissions easily quantified)	Requires Research (Socio-economic costs may be considerable. Support of alternative land management options, though potentially funded through CAP, must be considered)	Easy (Livestock removal is easy. Cross Compliance and farm biodiversity or landscape preservation may require maintenance of some livestock and associated land management. However, there may be considerable social implications if encouraged without sufficient support and cognisance of a just transition)	
Extending Grazing Season	0.065 Mt CO_2-eq [a]	Easy (Activity data captured in National Farm Survey while manure emissions captured within the inventory)	- €96 per t CO_2-eq [a]	Moderate (Careful management and associated knowledge of soil structure required)	
Dietary Additives and Vaccines	Requires Research	Difficult (Emission factors regarding additives and vaccines requires research)	Requires Research	Moderate (Opportunity for administration of additives may be limited)	
Genetic Efficiency (increased use of breeding indices)	Beef Genomics - Maternal) 0.025 Mt CO_2-eq [a] (Beef Genomics - Live weight) 0.061 Mt CO_2-eq [a] (Dairy EBI - Production) 0.43 Mt CO_2-eq [a]	Difficult (No methodology exists relating to genetic traits or associated activity data. Theoretically, new classes of animals, considering traits would need to be researched, defined and validated)	(Beef Genomics - Maternal) - €602 per t CO_2-eq [a] (Beef Genomics - Live weight) - €215 per t CO_2-eq [a] (Dairy EBI - Production) - €200 per t CO_2-eq [a]	Moderate - Difficult (Artificial insemination may require greater management, time and infrastructure, regarding heat observations, cattle handling and associated facilities)	
Optimised Herd Health	0.131 Mt CO_2-eq [a]	Moderate (Indirectly captured through animal type and age class)	- €46 per t CO_2-eq [a]	Moderate (May require knowledge transfer and management changes)	

Table 9. (Continued)

Measure	Predicted Annual Effectiveness	Ease of Inventory Capture	Estimated Annual Cost	Ease of Deployment (Opportunity Costs)	Overall Rating
Nitrogen Fertiliser Formulation (Substitution of CAN on grasslands)	0.521 Mt CO_2-eq [a]	**Easy** (Emission factors are established for protected urea while activity is easily quantified)	€8.31 per t CO_2-eq [a]	**Easy** (Substitution of CAN with protected Urea should not require major changes in management. Also, it is easy to mandate. However, research to ensure low-risk of residues is required before encouraged substitution)	
Multi-species Swards (reduced nitrogen fertiliser use)	(Clover in swards) 0.069 Mt CO_2-eq [a]	**Easy - Moderate** (Benefits only captured indirectly through activity data regarding N fertiliser use)	- €6.9 per t CO_2-eq [a]	**Moderate** (Establishment should be straight-forward. However, changes in soil fertility, grassland management and associated knowledge is required)	
Soil Fertility Management	(Optimized soil pH) 0.112 Mt CO_2-eq [a]	**Easy - Moderate** (Emissions related to fertility management (e.g. liming) easily captured. Benefits of improved fertility captured indirectly through reduced fertiliser use)	- €124 per t CO_2-eq [a]	**Easy** (The means of soil fertility optimization straight-forward and well established. Despite this, considerable behavioral barriers exist which need to be addressed)	
Low Emission Slurry Spreading	0.117 Mt CO_2-eq [a]	**Easy** (Emission factors for different spreading methods are established with activity data capture in TAMS applications and the National Farm Survey)	€187 per t CO_2-eq [a]	**Easy** (Minor changes in management may be required regarding timing of application)	
Soil Structure and Drainage (compaction prevention and drainage of wet mineral soils)	(Compaction prevention) Requires Research (Drainage of wet mineral soils) 0.197 Mt CO_2-eq [a]	Compaction prevention: **Difficult** (Quantification of compaction and emissions is difficult. Drainage: **Moderate** (N_2O emission factors regarding soil drainage class developed, though activity data is difficult).	(Compaction Prevention) Requires Research (Drainage of wet mineral soils) €16.2 per t CO_2-eq [a]	Compaction prevention: **Easy to Moderate** (Requires knowledge and changes in management) Drainage: **Difficult** (Installation of drainage systems expensive and requires expert advice)	

Table 10. Summary and classification of mitigation measures with regard to perceived attributes (Carbon Sequestration in Soils & Biomass)

Measure	Predicted Annual Effectiveness	Ease of Inventory Capture	Estimated Annual Cost	Ease of Deployment (Opportunity Costs)	Overall Rating
Stock and Sequestration in Grasslands (in mineral soils)	(Assuming improved management of 450,000 ha) 0.262 Mt CO_2-eq [a]	**Difficult** (Quantification of grassland emissions is straightforward, however changes associated with altered management requires research and verification)	- €41 per t CO_2-eq [a]	**Moderate** (Changes in management and associated knowledge may be required)	
Afforestation	(Assuming planting rate of 7,000 ha yr^{-1}) 2.1 Mt CO_2-eq [a]	**Easy** (Emission factors for forestry and methods for quantification of activity are well established)	€45 per t CO_2-eq [a]	**Difficult** (Relatively straight-forward to manage. However, there are considerable behavioral / social barriers to adoption that need to be addressed)	
Agroforestry	Requires Research (Considerable benefits other than mitigation, e.g. an enhanced natural environment and climate change adaptation)	**Moderate** (Emission factors for specific tree species established. Activity data captured within the National Forest Inventory. Further research regarding Irish specific agroforestry systems required	Requires Research (Co-benefits regarding an enhanced natural environment must be considered)	**Difficult** (Requires new management practices and associated knowledge transfer. On-farm infrastructural changes may be required. There may be behavioral / social barriers to adoption.	
Small-scale Native Woodlands	Requires Research (Considerable co-benefits including an enhanced natural environment and climate change adaptation)	**Easy - Moderate** (Activity should be captured within the National Forestry Inventory or scheme registration and Land Parcel Information System)	Requires Research (Financial support regarding implementation and losses associated with reduced farmland area and production must be considered)	**Moderate** (Establishment and management is relatively straight-forward, while co-benefits may encourage adoption. However, reductions in farmland may act as a barrier to adoption if not adequately supported)	

Table 10. (Continued)

Measure	Predicted Annual Effectiveness	Ease of Inventory Capture	Estimated Annual Cost	Ease of Deployment (Opportunity Costs)	Overall Rating
Farm Hedgerows (improved management)	Requires Research (Previously estimated to sequester in existing condition 0.27-1.4 Mt CO_2-eq [b])	**Difficult** (Research is required into sequestration associated with management changes along with baseline data for existing hedgerows)	Requires Research	**Moderate** (Hedge laying, coppicing and replacement where appropriate requires knowledge, management and is time consuming. Without schemes it is costly)	
Grasslands (water table manipulation)	(Assuming complete cessation of drainage on 40,000 ha) 0.44 Mt CO_2-eq [a]	**Moderate** (Emission factors are established for wetlands, however activity data may be difficult to acquire)	€10.9 per t CO_2-eq [a]	**Moderate** (Drainage may be stopped by allowing existing systems to block. However, reductions in, or elimination of agricultural activity may act as a behavioral / economic barrier if not sufficiently compensated)	
Forestry (Re-planting or re-wetting)	Requires Research (This is site dependent)	**Easy** (Emission factors and activity data are in use for forestry, while emission factors for potential re-wetting are established)	Requires Research	Re-planting: **Easy** (Re-planting is mandatory and so no changes in management required) Rewetting: **Moderate** (Takes site specific management and knowledge)	
Cutaway & Cutover Peatlands	This is site-specific	**Easy** (Emission factors are established for re-wetting and activity should be easily quantified)	€4 per t CO_2-eq [c] (This is site-specific and assuming no opportunity costs associated with retiring harvesting at an accelerated timeframe)	**Moderate** (Re-wetting requires site specific management, monitoring and associated knowledge. Likely impacts on the wider catchment must also be examined)	

Table 11. Summary and classification of mitigation measures with regard to perceived attributes (Reducing Agricultural Emissions)

Measure	Predicted Annual Effectiveness	Ease of Inventory Capture	Estimated Annual Cost	Ease of Deployment (Opportunity Costs)	Overall Rating
On-farm Energy Saving	(Assuming 0.029 Mt CO_2-eq [a]	**Easy** (Emission factors and activity data captured under existing inventory methodology)	- €359 per t CO_2-eq [a]	**Moderate** (No changes in management necessary though there may be behavioral and economic barriers to adoption, the latter regarding initial capital costs)	
Energy from Biomass	(Energy from Wood Biomass) 0.759 Mt CO_2-eq [a] (Heat from Short Rotation Coppice) 0.179 Mt CO_2-eq [a] (Electricity from Short Rotation Coppice) 0.187 Mt CO_2-eq [a]	**Easy** (Emission factors and activity data captured under existing inventory methodology)	(Energy from Wood Biomass) - €30.7 per t CO_2-eq [a] (Heat from Short Rotation Coppice) - €20 per t CO_2-eq [a] (Electricity from Short Rotation Coppice) - €10 per t CO_2-eq [a]	**Difficult** (Likely to be barriers to adoption due to market demand instability in the past)	
The Bioeconomy and Circular Bioeconomy	Requires Research	**Easy - Moderate** (A whole systems approach is necessary. The inventory captures where fossil recourses are used within the supply chain while biomass and energy are already captured) (The National accounts may form a better metric regarding the GHG and energy efficiency of the circular bioeconomic)	Requires Research (Different products within different streams in the circular bioeconomy makes calculation of costs complicated. Measurement will be by comparison with the carbon economy)	**Difficult** (Development of the bio- and circular bioeconomy will cause disruptive change to existing whole economy)	

[a] According Lanigan *et al.* (2018). Mean annual values estimated over a ten year period and assuming linear adoption.

[b] According to Black *et al.* (2014) [c] According to Renou-Wilson *et al.* (2018)

4 Discussion and Conclusions

This review of existing literature and collation of expert opinion has identified a clear and urgent need for changes in management and associated policy within the AFOLU sector. The need for change also presents considerable opportunity, not only in combatting climate change, but also making the sector more sustainable, bringing multiple co-benefits to society.

Agricultural systems, the predominant land use, are: causing significant greenhouse gas emissions; in certain cases, adversely impacting Ireland's natural environment; often generate poor economic returns and are subject to external drivers creating incentives for expansion. The environmental, economic and social sustainability of many current agricultural systems and practices in Ireland needs to be assessed. Farmers, as key land managers, have successfully responded to policy, market and institutional signals in the past, and will form a key part of the solution. Conflicting communication, policy and incentives within the agricultural sector, further exacerbate issues. Afforestation rates are substantially below target, while organic soils are a significant source of carbon emissions.

The following mitigation options to should be considered:

1. A gradual reduction in national bovine numbers may be necessary to achieve greenhouse gas emission reduction. This may also help address localised environmental degradation if implemented appropriately. Further expansion of the dairy herd may increase the risk of additional adverse environmental impacts. Continuation of the observed decline in suckler cow numbers, in conjunction with stabilisation of dairy cow numbers, would represent an important contribution to national efforts to reach Effort Sharing Regulation targets. Any reductions in animal numbers should be facilitated by long-term and consistent supports for stable incomes to provide favourable environmental outcomes through land management.

2. Management options for wetlands, especially peatland, require urgent assessment and implementation. Time is of the essence, as it will take a number

of years for peatland ecosystems to re-establish and built resilience to projected changes in climate. The drainage of peat for multiple land uses, including peat extraction, must cease. Areas for rewetting should be identified and associated land management programmes started. Identification of agricultural land on which drainage has already ceased is required for inventory accounting. Bord na Móna's plans for peatlands under its management are an important opportunity for leadership, learning and public engagement.

3. Low afforestation rates need to be addressed with recognition and consideration of behavioural barriers. The type of afforestation, in terms species and environmental impacts, needs to be considered. Agroforestry appears to be a resilient system that permits agricultural production with limited afforestation, bringing multiple co-benefits and with further research, should be encouraged.

4. Expanding on approaches in the National Planning Framework, there is merit in the development of a national land use strategy. This should not be prescriptive but would enable design of policy to promote the sustainable delivery of multiple and competing land functions, while ensuring long-term environmental sustainability.

5. Cost-effective mitigation measures, identified in the Teagasc Marginal Abatement Cost Curve analysis, should be implemented as appropriate. These mitigation options that would deliver reductions of 2.9 Mt CO_2-eq per year, by 2030. The Common Agricultural Policy provides the mechanism for aiding this as it moves to greater national control.

6. There is a need for specific research into mitigation options that are detailed in this paper. Research requirements concern existing mitigation measures, the development of new measures, their technical implementation, impacts or trade-offs and associated development and refinement of inventory accounting methodologies.

7. Adoption and successful implementation of climate change mitigation policy and measures depends on farmers' acceptance based on their lived experience,

knowledge and understanding. Additional research and resources to enable effective knowledge exchange are required.

8. Noting the success of participatory approaches to engagement, for example the Citizens' Assembly, a process of co-design could be implemented to facilitate engagement and ultimately strong stakeholder ownership of mitigation policies, which would help to achieve a just transition.

9. Identification and review of existing incentives and schemes that may be in conflict with greenhouse gas mitigation objectives is required, as coherence in policy is vital.

10. Ireland needs to engage with national and international experts to demonstrate and validate its environmental sustainability or 'green' credentials regarding food production.

11. Ireland should continue to support research into balance and neutrality concepts while promoting international research and policy development on this topic. Specifically, regarding the development of metrics that appropriately account for the lifetimes of short-lived greenhouse gases, such as methane.

Finally, it must be emphasised that many climate mitigation measures within the AFOLU Sector generate additional co-benefits, including biodiversity, ecological interaction, enhanced air quality, landscape protection, recreation and tourism potential, economic diversity and human wellbeing. Such benefits are associated with economic, environmental and social sustainability and represent the result of good land stewardship.

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APPENDIX 1.

Supporting Notes on Key Land Use types in Ireland

A.1.1 Wetlands

In Ireland, peatlands have the highest storage capacity, especially pristine raised bogs. The limiting factor for peat depth tends to be a combination of local topography, hydrology and climate conditions. Drainage of peatlands, for whatever purpose, is a significant source of carbon dioxide emissions. The rate of carbon loss due to drainage can be an order of magnitude greater than rates of carbon sequestration of pristine or restored peatlands. Management of the water table, including rewetting, can curtail these emissions.

Although uncommon, pristine peatlands in Ireland appear to be still in a growth phase, with peat formation conditions occurring in most years. However, dry, warm conditions have been observed to lead to carbon losses from peatlands. The average rate of carbon uptake in a pristine blanket peatland was 0.3 t C ha^{-1} yr^{-1} (Kiely *et al,* 2018, Renou-Wilson *et al.,* 2011). The large majority of peatlands in Ireland are in a degraded state, often as a result of historic disturbance and exploitation. Nevertheless, degraded peatlands remain the largest store of carbon is the Irish landscape. There are two broad categories of degraded peatlands, areas which are subject to on-going active management and drainage; and areas where there is no longer active management, but have been drained and exploited in the past. There are limited data on the condition of degraded bogs, and general conclusions on whether they are losing carbon, or have reverted or recovered to a growth phase are not possible. Re-establishment of much of the biodiversity of the habitat is possible on rewetted degraded peatland in a relatively short period. Recovery of peat formation takes longer to establish and the carbon stocks are more vulnerable to inter-annual variability than pristine peatlands. Therefore, it is generally inappropriate to suggest that restoration and rewetting of drained organic soils would deliver significant carbon sequestration on timescales relevant to the requirement to mitigate national greenhouse gas emissions. Of greater importance is the opportunity to avoid the loss of carbon due to drainage. Pristine and restored peatlands are a source of methane emissions. The rate of emission of methane can depend on a wide variety of factors including water table, plant species and temperature. Where restoration of peatland habitat is the objective, methane emissions are unavoidable but can be viewed as a necessary characteristic of the ecosystem, and in the long term will be offset by the gradual sequestration of atmosphere carbon dioxide into new peat. Although, water table management cannot be guaranteed to restore carbon sequestration function to peatlands, it is a very effective means of reducing carbon losses.

Rewetting to manage carbon losses does not require restoration. It may be possible, and indeed preferable at some sites, to actively manage the water table to curtail carbon losses, whilst maintaining a shallow depth of drained soil. This aerated, surface layer can effectively oxidise the methane emerging form the rewetted layers below. This may be a useful option for management of drained organic soils where restoration is not feasible.

A.1.2. Grasslands

Grasslands are the second largest carbon stock, due to the large area and high soil carbon content. There is evidence that grazing pastures managed to maintain typical livestock stocking rates (1.0 to 2.0 Livestock Units ha^{-1}) tend towards higher soil carbon content relative to low intensity grazing systems. There are limits to the sustainable level of intensification, with high stocking rates leading to a decline in soil carbon (Muhammed, *et al.,* 2018, Abdalla *et al.,* 2018). Additional caution is required in moving towards optimised production intensity within grassland-based livestock systems. In many instances the improved production is achieved with greater use of synthetic nitrogen fertilisers. This will lead to the emission of nitrous oxide. There are options to reduce the emission of nitrous oxide, including alternative formulations of fertilisers, mixed swards incorporating clover, and actions to improve other aspects of soil fertility such as pH, potassium and phosphorous.

Teagasc have reported decline in soil quality and currently Irish soils have significantly sub-optimal soil fertility (Teagasc, 2017). An expert statement from the Royal Irish Academy suggests that Irish agricultural soils have considerable potential for additional carbon sequestration which may be realised through improved land management (Kiely, 2016 as cited in RIA, 2016).

Traditionally, grasslands are managed to provide grazing and fodder for livestock. Much of the area of grassland are actively grazed, which enables high rates of nutrient and carbon recycling to soils. However, a large area of grassland is harvested to provide winter fodder, mainly silage. This harvesting of grass removes biomass from the fields.

Some is recycled through later spreading of slurry. This may be of increasing concern if other economic uses of grass biomass emerge, such as anaerobic digestion generation of biogas from feedstock such as grass.

Approximately 300,000 hectares of agricultural grasslands occur on drained organic soils, converted from peatlands, and as such as subject to significant losses of carbon. Currently, the default IPCC emission factor for carbon losses from nutrient poor drained organic soils is applied to estimate the emissions from these areas in the national inventory (Duffy *et al.,* 2018). However, there is evidence that these lands are managed with relatively shallow water table, leading to observed lower emission rates than the IPCC default value (Renou-Wilson *et al,* 2015).

A.1.3. Croplands

Croplands tend to have the lowest soil carbon content, as oxidation of soil carbon is enabled by repeated disturbance and exposure to air during tillage. This project has established a robust methodology for tracking the management of croplands on a land parcel scale on an annual basis. However, additional research and monitoring is required to provide country specific analysis of the impact of land management practices on emissions. Greenhouse gas mitigation options for croplands include improved nutrient management, straw incorporation and the establishment of catch or cover crops (Eory *et al.,* 2015; RICARDO-AEA, 2016; Lanigan *et al.* 2018). As mentioned, catch crops are established after harvest of principle crops to provide ground coverage and intercept availed soil nutrients, thus preventing leaching and run-off. Teagasc identified cover crops and straw incorporation as having potential, at estimated costs of €86 and €279 t CO_2-eq mitigated respectively. Cover crops may reduce nitrogen leaching (Premrov *et al.,* 2014) and therefore, indirect nitrous oxide emissions, while facilitating carbon sequestration (Poeplau & Don, 2015). Cross Compliance regulations require the establishment of sown green cover within six weeks of ploughing arable land and sown or naturally regenerated green cover within six weeks of spraying non-selective herbicide. The voluntary Green Low-Carbon Agri-Environmental Scheme (GLAS) includes an option for catch crop establishment on a minimum of area of 4 hectares and maximum of 32 hectares.

A.1.4. Forest land

Forest land has the highest biomass per hectare. As noted, historically Ireland was largely denuded of native forest, and over 90% of existing forest area have been established since the beginning of the 20th century. The annual Forest Statistics from DAFM assign a large carbon stock of approximately 380 Mt C to forest land (DAFM, 2018a). However, country specific research has established that forest soils tend towards carbon contents that are similar to those of managed grasslands (Duffy *et al.,* 2018). Therefore, although it is correct to assign a large soil carbon stock to forest soils, the carbon is not as a result of afforestation, but consistent with maintaining an existing carbon stock in the transition from other land use to forest land. Afforestation is a central element of current land use policy, and it is the biomass component of the carbon stock which provides the main carbon removal option. There is a need for detailed scenario analysis to provide insight into the potential development of the forest carbon stock in response to emerging demands for biomass resources for energy, materials and other ecosystem services. For example, in the long-term, over the management cycle of a commercial plantation, the average carbon stock is approximately 60 t C ha^{-1}. If the total forest area increases to 1.2 million hectares, then the total sustainable national carbon stock in biomass would reach 70 Mt C, (260 Mt CO_2-eq) with a capacity of delivering 2.5 Mt C yr^{-1} of biomass to markets. This figure is greater than the current biomass stock, due to the larger area in this scenario, and the assumption of moving gradually to a uniform age profile. Currently, the national forest has an age profile skewed to less mature trees.

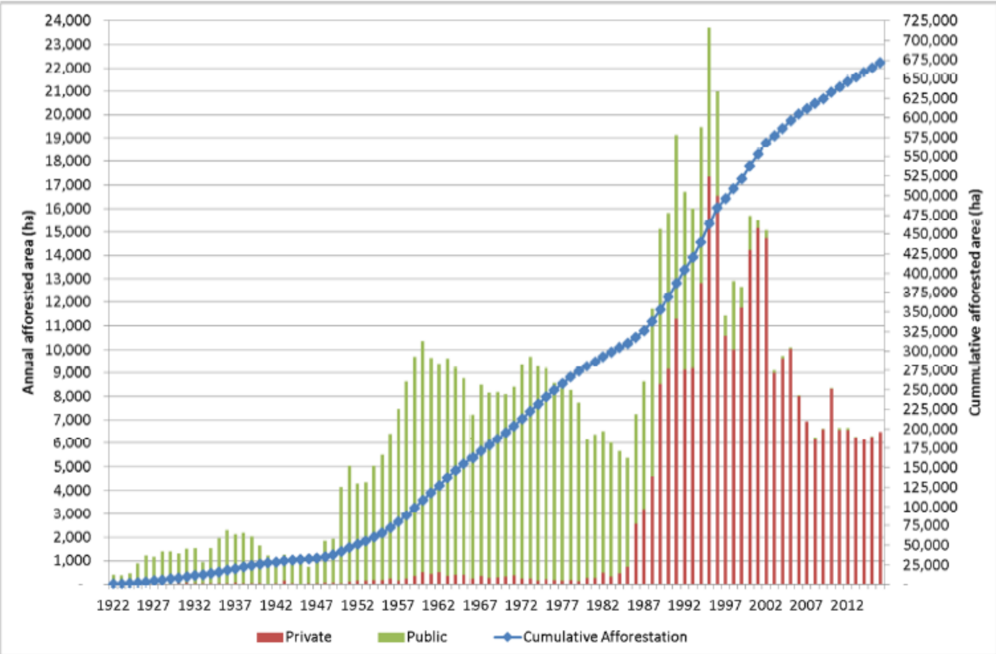

Figure 9 Annual State and private afforestation 1922-2016

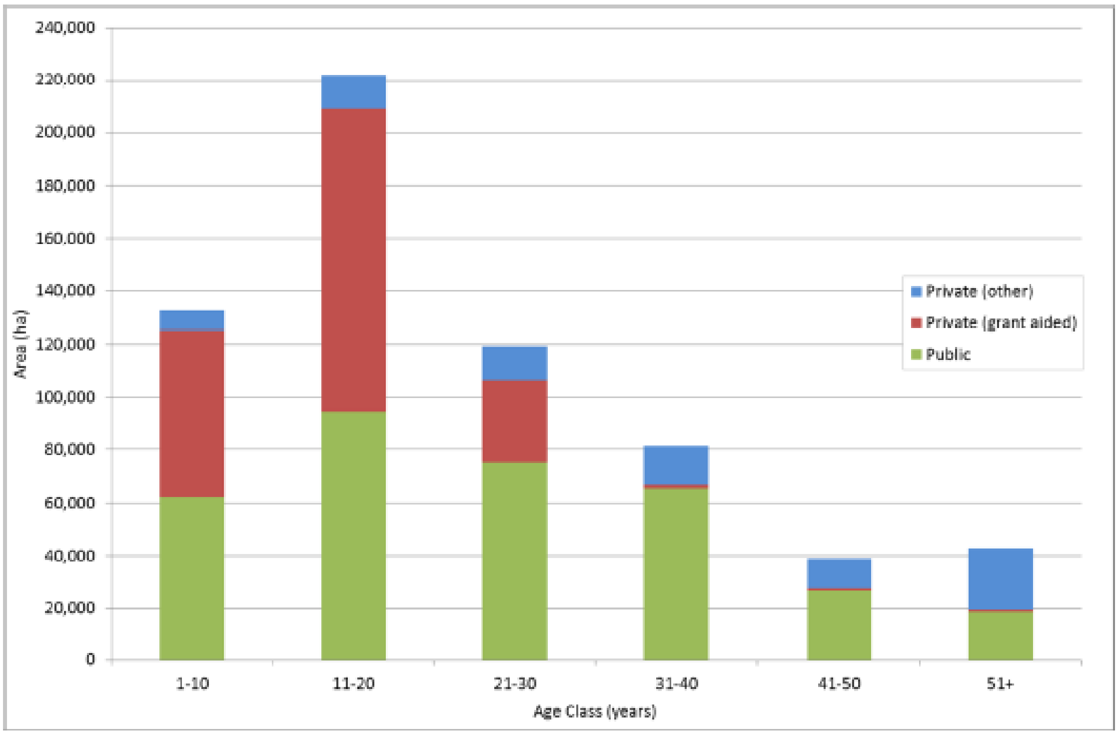

Figure 10 Forest age class distribution by ownership (Source National Forest Inventory, 2012), extract from DAFM Annual Forest Statistics, 2018

Irish forestry development is principally guided by Ireland's Forest Policy (DAFM, 2014) and is expanded on by the Forestry Programme 2014-2020 (DAFM, 2015c) with regard to EU Regulation 1305/2013 concerning rural development. The former policy document outlined a forestry expansion aim of 10,000 ha yr^{-1} to 2015 and 15,000 ha yr^{-1} from 2016 to 2046, which would increase forest cover to 18% (1.25 million hectares). Forestry cover is currently 11% (DAFM, 2018a). The Afforestation Grant and Premium Scheme 2014-2020, under the Forestry Programme, aims to support the increase of national forest cover to 18% by 2046, with aimed establishment rates for new forest of 10,000 ha yr^{-1} (DAFM 2015d). Within this schemes' timeframe (to 2020), 30% of the area afforested aims to be under deciduous trees with general encouragement of planting on better land. Mean afforestation rates of 7,674 ha yr^{-1} occurred between 2012 and 2017 (DAFM, 2018a). It is highly unlikely that the 18% forestry cover target by 2046 will be achieved.

APPENDIX 2.

Supporting Notes on AFOLU Mitigation Strategies

A.2.1. REDUCTION OF AGRICULTURAL GREENHOUSE GAS EMISSIONS

A.2.1.1. Greenhouse gas emissions from livestock

A Gradual Reduction in Bovine Numbers

The impact of bovine numbers on agricultural and national greenhouse gas emissions has been outlined (Sections 2.2 and 3.1.1.). According to Duffy *et al.* (2019), methane emissions from bovines alone (enteric fermentation and manure deposition and management), accounted for 85.6% of total national methane emissions (excluding LULUCF), 61.3% of total agricultural emissions and 19.7% of total national greenhouse gas emissions in 2017 (excluding LULCF). A current trend of increasing agricultural emissions was principally attributed to increasing bovine numbers (EPA, 2018a; EPA, 2018b), with emission projections to 2030 determined accordingly (Lanigan *et al.,* 2018). The EPA has identified increasing bovine numbers as also largely responsible for increasing ammonia emissions and failure to meet national emission targets (EPA, 2018d). Additionally, and though not directly attributed to bovines, agriculture is identified as negatively impacting Irish river water quality (EPA, 2016; EPA, 2018e) as well as threatening biodiversity (DCHG, 2017a). Bovine systems form the principle agricultural activity in Ireland (Dillon *et al.,* 2018; CSO, 2018a) and are therefore likely to be a key driver of current environmental degradation.

The 2017 national farm survey (Dillon *et al.,* 2018) indicated an average increase in national farm income, attributed largely to gains made in the dairy sector. Cattle rearing, principally from suckler herds, was identified as generating the lowest average farm income (€12,529) in 2017 and remained relatively unchanged since 2016Roughly half of cattle farms earned < €10,000 in 2017 with heavy reliance on subsidies. Direct payments contributed to 114% and 96% of income for cattle rearing and cattle finishing enterprises respectively. This is compared to the dairy sector, where direct payments contributed to 22% of farm income. Therefore, not only do direct payments account for the entire farm income of cattle rearing enterprises, but for every €100 received, €14 was lost to subsidise production. When direct payments were discounted, cattle rearing on average was found to make a loss per unit of product, or the cost of production exceeded market income (Dillon *et al.,* 2018). Cattle finishing was estimated to generate small profits, though for every €100 received in income, €4 represented market income and €96 - direct payments. Overall, Buckley *et al.* (2019) indicated that only roughly 25% of beef enterprises (including both cattle rearing and finishing) were economically viable.

It is therefore suggested that overall, current national bovine numbers are environmentally and, economically unsustainable. A gradual reduction may be necessary, and further expansion of the national herd should not occur.

Where production does not exceed environmental limitations at farm and catchment scales, there is justification for maintenance of the dairy herd at current levels. Expansion within the dairy herd should only take place where within environmental limitations. It is difficult to envision further expansion of the dairy herd within environmental constraints. As beef production is largely dependent on direct payments (Dillon *et al.,* 2018; Dillon *et al.,* 2019), it may be appropriate to focus a potential gradual number reduction within the beef sector. Following the introduction of the EU Milk Quota in 1984, expansion of the national beef herd occurred (Hennessy & Kinsella, 2013). The abolition of the Milk Quota in 2015 facilitated the expansion of the dairy herd (Läpple & Hennessy, 2012), with little re-adjustment within the overall beef sector evident (CSO, 2018a). However as discussed and outlined in Figure 1 (Section 2.2), a decline in suckler cow numbers has occurred in tandem with increasing dairy cow numbers, though expansion of the dairy herd is proportionally greater than reductions in the suckler herd. Lynch *et al.* (2016b) projected a likely decline in suckler cow numbers nationally and a 5% reduction in Irish beef exports by 2030 compared to 2015 under a modelled baseline projection. It is emphasised that any gradual reduction within the beef herd and associated release of land, may in the first instance support alternative land use, including afforestation, and should not facilitate dairy herd expansion and where so, only if environmentally appropriate. There is recognition that dairy systems, which are typically intensive, generate greater emissions than beef systems (Lynch *et al.,* 2016a; Buckley *et al.,* 2019; Tzemi & Breen, 2019). With regard to extensification, suckler cow number reductions may not be appropriate where low stocking rates, or extensive systems already exist. The potential importance of such systems in supporting important habitats and associated biodiversity (NWPS, 2013; Sheridan et al. 2017) has been discussed (Section 2.2).

From a greenhouse gas emissions perspective and in the absence of other agricultural mitigation measures, the theoretical impact of a gradual reduction in suckler cow numbers and stabilisation of the dairy herd has been explored through three simple scenarios for the period out to 2030 (Section 3.1.1). Scenario A indicated that a 15% reduction in the suckler herd equated to an increase in total agricultural emissions by 2.9% relative to 2005 in 2030. Scenario B explored the impact of a 30% reduction in the suckler herd by 2030 which equated to a reduction in total agricultural emissions by 0.9% relative to 2005. Finally, Scenario C indicated that a reduction of the suckler herd to pre-Milk Quota levels (1984 levels), equated to a 45% reduction in suckler cow numbers relative to 2018 levels, and could lead to a 6.7% reduction in total agricultural emissions relative to 2005 in 2030. For all scenarios it was assumed that dairy cow numbers remained at 2018 levels (1.4 million animals) though milk yields and associated feed intake was projected to increase to 2030. Emission factors were adjusted accordingly. The associated reductions in follower heifers and in cattle of different age classes has been accounted for along with changes in methane and nitrous oxide emissions from manure management and deposition. Total sheep and pig numbers were adjusted to Teagasc baseline scenario (S1) projections (Donnellan *et al.,* 2018; Lanigan *et al.,* 2018) while nitrogen fertiliser use was assumed to stabilise at projected 2018 levels.

Total agricultural emissions in 2005 were 18.7 Mt CO2-eq (Duffy *et al.,* 2019). In the absence of sector-specific emission reduction targets, Lanigan *et al.,* (2018) analysed a reduction in agricultural emission of 20% relative to 2005, equal to an emissions reduction of 3.7 Mt CO_2-eq by 2030. The same study identified cost effective agricultural mitigation options which would deliver 2.9 Mt CO_2-eq by 2030. This combined with a gradual reduction in suckler cow numbers would represent an important contribution to national efforts to reach Effort Sharing Regulation targets.

Policy intervention may be required to enable continued suckler cow number reductions. Despite previous incentives, such as decoupling within the CAP to facilitate number reductions, little change has been observed in overall beef livestock numbers (Figure 10).

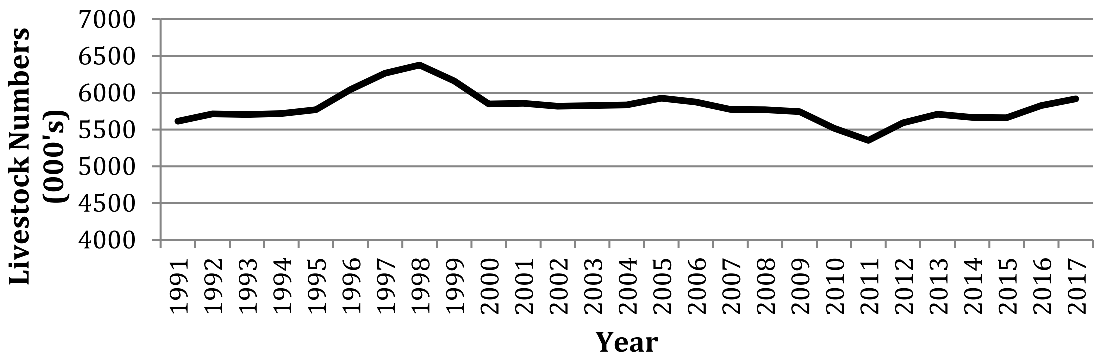

Figure 11 Beef livestock (non-dairy cows and cattle) numbers (Extracted from EPA emission inventory CSO Tables)

Buckley *et al.* (2019) explored the economic and environmental impact of the various beef production systems prevalent in Ireland. The study noted a positive correlation between emission efficiency and economic performance. Using IPCC guidelines, the top economic performing farms emitted less (9.6 kg CO_2 kg beef^{-1}) than bottom performing enterprises (14.9 kg CO_2 kg^{-1} beef^{-1}). However, despite slightly better nitrogen use efficiency, nitrogen surpluses were found to be higher on better performing farms (89.7 kg N ha^{-1}) compared to bottom performers (47.8 kg ha^{-1}) due to the system intensity. As discussed, less-intensive systems may also support wider eco-system services. Using High-Nature-Value (HNV) farming as an indicator, regions associated with lower agricultural economic performance are identified as having greater value (Finn, 2016;

EPA, 2016). The important role of less-intensive systems in supporting wider eco-system services, including landscape aesthetics is perhaps highlighted by the Burren Programme (NESC, 2016). Indeed, the maintenance of traditional farm landscapes was found to be publicly supported (Howley *et al.,* 2012). From a local environmental and landscape perspective, reductions in bovine numbers on less-intensive systems may not be appropriate, notably if changes facilitate more intensive systems such as dairy production.

In addition to local environmental considerations, the likely negative socio-economic and cultural, impacts of a reduction in bovine numbers must be recognised. Progressive elimination of the Irish suckler herd to 2030 was estimated to cause a 14% reduction (from a projected baseline) in beef exports (Lynch *et al.*, 2016b). Lanigan *et al.* (2018) warned of disproportional social and economic implications of a reduction in the national herd. Indeed, beef farmers receive some of the lowest farm incomes (Dillon *et al.,* 2018). From a social perspective, 23% of beef farmers were identified as living alone and therefore, at risk of isolation. Roughly, 32% of enterprises had an age profile above 60 with no other member of the household less than 45 years old. Both isolation and age profile were negatively correlated to economic performance (Buckley *et al.,* 2019). Indeed, the average age of beef rearing and beef finishing farmers was 56 and 57 years respectively (Dillon *et al.,* 2018). A survey of small farms (where standard output = ≤ €8,000 per annum), of which cattle enterprises represent 61%, indicated that 32% were farmed by people ≤ 65 years while 28% were single person households (Dillon *et al.,* 2015). The encouragement of a reduction in suckler cow numbers must be only with full cognisance of a just transition, and government accordingly (see Section 3.4.4).

Hennessy *et al.* (2018) discuss the contribution of the suckler beef sector to, not only the export industry but also rural economies. Roughly €1.5 billion was estimated to be spent per annum on agri-products by cattle farmers predominantly in rural economies with positive multiplier effects greater than other sectors. Suckler farming clearly has social benefits, notably in isolated rural regions (Hennessy *et al.,* 2018). Any encouragement of changes in cattle production warrants carful research into socio-economic impacts.

Elimination of the suckler herd was envisioned to impact land markets and other agricultural activity, potentially facilitating increased dairy production (Lynch *et al.,* 2016b). Additionally, if a proportion of farms exit beef production for afforestation, an intensification of remaining beef farms may occur, therefore maintaining beef numbers and generating localised pollution. Casey & Holden (2006a) suggested that the integration of the dairy and beef systems is important in combatting livestock emissions. From and LCA perspective, emissions allocation can potentially be reduced by over 30% if beef animals are produced from dairy rather than suckler cows. Styles *et al.* (2017) projected increased emissions associated with the intensification of milk production in the UK that led to reduced dairy-beef output and increase reliance on suckler herds for beef production. The optimisation of dairy-beef production systems is clearly desirable, though analysis of the extent to which this is possible and its likely contribution to greenhouse gas mitigation is required. Additionally, contract rearing of dairy herd stock by beef enterprises may be beneficial. Barriers to integration between the two systems may include necessity, proximity of enterprises, land availability, biosecurity and attitudinal motivation or preferences.

Extended grazing season

Production of methane by enteric fermentation is caused by methanogenic bacteria working principally in the rumen, on hydrogen (H_2), a product of primary and secondary digestion. Hydrogen is associated with the production of volatile fatty acids (VFAs) notably, acetate. Other volatile fatty acids include propionate and butyrate. Feed materials that have a higher level of cellulose or structural carbohydrate, lead to a greater proportion of acetate production and potentially greater methane emissions (Boadi *et al.,* 2004). As mentioned, grass accounts for 80 to 90% of the diet of beef and dairy cattle in Ireland (EPA, 2016). Conserved grass (i.e. silage or hay) typically has a higher proportion of cellulose compared with freshly grassed grass, and therefore may generate higher methane emissions, though impacts may vary (Martin *et al.,* 2010). Teagasc recommend extending the grazing season, which allows greater utilization of fresh grass and less silage intake (Lanigan *et al.* 2018). Grazing season length is also identified within the Carbon Navigator package (DAFM, 2018). Extending the grazing season may require the implementation or renovation of land drainage systems, as soil compaction from livestock treading is likely if soils are wet (Houlbrooke & Laurenson, 2013; Drewry, 2006) later in the season. However drainage must only be conducted where appropriate. The drainage of organic soils is discouraged regarding carbon dioxide emissions (Renou-Wilson *et al.,* 2015) as discussed later. Extending the grazing season may also reduce the quantity of slurry stored, further reducing emissions, though increased dung and urine deposition on grassland particularly when soil moisture content is high, may lead to increased nitrous oxide emissions (Ball *et al.,* 2012).

Dietary additives and vaccines

Numerous measures regarding bovine diets have been investigated along with associated challenges (refer to Martin *et al.,* 2010). Teagasc explored the inclusion of lipids or fatty acids to dairy cow diets, which was estimated to mitigate 0.035 Mt CO_2-eq per annum, at a cost of €76.0 t CO_2-eq abated (Lanigan *et al.,* 2018). There are a number of other directly fed additives that may contribute to reducing methane emissions. The United Kingdom MACC identified nitrate and probiotics such as yeast culture (*Saccheromyces cerevisiae*) as potentials (Eory *et al.,* 2015). Research indicates that seaweed extracts may greatly reduce methane production (Machado *et al.,* 2014; Patra *et al.,* 2017) while the use of 3 - nitrooxypropanol (3-NOP), an enzyme inhibitor, has also shown promising results (Haisan *et al.,* 2014; Haisan *et al.,* 2016; Joyanegara *et al.,* 2018). Romero-Perez *et al.* (2015) observed methane emission reductions in beef cattle by 59% from feeding of 3-NOP in mixed rations at a rate of 2.0 g day^{-1} $animal^{-1}$. Reduced methanogenesis was sustained during the trial for 112 days.

Patra *et al.* (2017) note potential issues with such additives regarding inconsistent results or digestion and feed intake restrictions. In an Irish context, administration of additives may be daily and by bolus within total mixed rations. This may not suite grass-based systems, where opportunities to feed additives may be limited. Long-lived boluses that could be administered during milking, or during *ad libitum* feeding of intensive beef finishing, may have potential. Methane-inhibiting vaccines may negate the need for daily administration. The development of vaccines, which induce the production of methanogen inhibiting antibodies, potentially in the saliva and transported to the rumen, has proven extremely challenging but suggested to be possible (Wedlock *et al.,* 2013; Subharat *et al.,* 2016; Patra *et al.,* 2017). Interestingly, Hook *et al.* (2010) noted challenges associated with variation in methanogen populations as a result of livestock geographic location and associated feed. Research currently being conducted in New Zealand may provide useful insights (New Zealand Agricultural Greenhouse Gas Research Centre, no date).

Despite some of these technologies being commercially available, they appear not to be used currently in Ireland and warrant research, notably regarding side effects. However, dietary additives and the use of vaccines may have considerable potential.

Genetic efficiency

Breeding for bovine production efficiency may reduce greenhouse gas emission per unit of output (Schils *et al.,* 2013; Pickering *et al.* 2015). Pickering *et al.* (2015) suggest genomic breeding values offer a sustainable means of reducing ruminant methane emissions. In Ireland, there are a number of breeding indices that currently operate to increase genetic merit for productive efficiency and therefore economic gain but have potential to be used to reduce greenhouse gas emissions (Quinton *et al.,* 2018). These include the Economic Breeding Index (EBI) for dairy cattle (ICBF, 2013) and the Terminal (T), Maternal Replacement (MR) and Dairy Beef (DB) Indices for beef cattle (McHugh & McGee, 2016). Both the Terminal Index and Replacement Index are incorporated in the Beef Data Genomics Programme (BDGP) (DAFM, 2018c). Established under EU Commissions approval, BDGP provides direct grant aid to farmers with the partial aim of specifically reducing greenhouse gas emissions (DFAM, 2018). Quinton *et al.* (2018) found both the beef MR and T Indices reduced system gross emissions (kg CO_2-eq breading cow) and the emissions intensity (kg CO_2-eq kg meat breading cow). The MR Index was important for both the gross emissions and emissions intensity, notably traits including cow survival (reducing the number of replacements) and cow live weight (less feed for maintenance of mature cows), though benefits may be offset by shorter calving intervals, increasing feed requirements. The T index was important for emission intensity regarding traits for meat production efficiency.

Lanigan *et al.* (2018) estimated that selection of favourable traits including feed consumption and methane emissions through the Maternal Replacement Index, could reduce greenhouse gas emissions by 0.81 kg CO_2-eq breeding cow yr^{-1} € index, or form a system perspective, emission intensity could reduce by 0.0089 kg CO_2-eq kg meat breeding cow yr^{-1} € index. This was under the assumption that 65% of beef farmers enter into the BDGP. Regarding improved terminal traits, Lanigan *et al.* (2018) suggested emissions per unit of beef could potentially be reduced by 17% by enhancing traits such as daily live-weight gain.

Regarding dairy production, the use of EBI, may allow better utilisation of grass from earlier calving dates, improved herd health and reduced gulling and therefore, replacement rates. However, as Lanigan *et al.* (2018) point out, caution is required as any mitigation is dependent on the national herd numbers or the production level remaining static, as if not, absolute emissions would increase regardless of greater efficiency per cow. In terms of specific traits, Quinton *et al.* (2017) suggested compiling indices specifically concerning emissions but note that these may not be aligned with economic gains, with clear trade-offs between economics and greenhouse gas reductions. None the less, certain efficiency traits will reduce greenhouse gas emissions and potentially increase economic returns.

Herd health

Maintenance of animal heath is a recently recognised mitigation strategy (Schulte *et al.,* 2012, Eory *et al.,* 2015). Theoretically, the absence of disease ensures optimal livestock productive efficiency, thereby requiring less input per unit of product and untimely, generating less greenhouse gas emissions. Ruminants, often more exposed than monogastrics (Eory *et al*., 2015), are subject to numerous endemic, sometimes sub-clinical, diseases including Mastitis, Johnes disease, Salmonella, Bovine Viral Diarrhoea (BVD) and lameness (ADAS, 2015, Lanigan et al. 2018). In United Kingdom, ADAS (2015) estimated Johne's disease to cause a 25% increase in greenhouse gas emissions per 1000 l of milk produced and BVD, a 130% increase in emissions per 100 kg of beef carcass weight. Mostert *et al.* (2018) found foot legions to lead to greater greenhouse gas emissions per unit of milk. The impact of digital dermatitis, white line disease and solar ulcers were collectively found to increase emissions per ton of fat and protein corrected milk by 14 kg t CO_2-eq (Mostert *et al.,* 2018). Hospido & Sonesson (2005) found mastitis to contribute to greenhouse gas emissions through the discarding of affected milk. In addition to endemic diseases, it is now recognised that improvements in general animal welfare may also contribute to reducing greenhouse gas emissions (Herzog *et al.,* 2018).

A.2.1.2. Greenhouse gas emissions from soils

Nitrogen fertiliser formulation

Grazed grasslands are highlighted as a nitrous oxide source as a result of enhanced microbial activity, associated with carbon input from decaying surface vegetation and dense root-mats (Schaufler *et al.,* 2010), with rhizosphere plant and microbe interaction an important factor in emissions (Butterbach-Bahl *et al.,* 2013). Harty *et al.* (2016) demonstrated that the type of fertiliser applied significantly impacts nitrous oxide emissions in temperate grasslands. Three forms of nitrogen fertiliser are currently used in Ireland (Duffy *et al.,* 2018). Calcium ammonium nitrate (CAN) is the principle form, accounting for 85% of nitrogen fertiliser sales in 2016, while urea and protected urea accounted for 14 and 0.5% sales respectively (Duffy *et al.,* 2018). This is in contrast to global nitrogen fertiliser consumption, which is urea dependant (Cantoarella *et al.,* 2018). Lanigan *et al.* (2018) advocated the replacement of CAN with urea, with the latter protected by nitrogen stabilizers. The form of nitrogen contained in urea (ammonium or NH_4^+) is less readily available for denitrification compared to nitrate (NO_3^-) contained in CAN (Roche *et al.,* 2016) and its use may lesson nitrous oxide emissions. Nitrogen stabilizers include nitrification or urease inhibitors (Watson *et al.,* 2009), typically dicyandiamide (DCD) and *N*-(*n*-butyl) thiophosphoric triamide (NBPT) respectively (Harty *et al.,* 2016; Roche *et al.,* 2016). Urea is associated with higher ammonia volatilisation (Forrestal *et al.,* 2017) with 16% of the N applied worldwide being converted to ammonia (Cantarella *et al.,* 2018). Ammonia may indirectly contribute to nitrous oxide emissions while also being an important air pollutant.

In light of the EU Emissions Ceiling Directive, requiring 1% and 5% reductions in ammonia emissions by 2020 and 2030 respectively (EPA, 2016), the protection of urea with a urease inhibitor is important, with NBPT commonly used (Harty *et al.,* 2016; Cantarella *et al.,* 2018) and the most promising (Forrestal *et al.,* 2016). Forrestal *et al.* (2016) observed a 78.5% reduction in ammonia emissions from the use of NBPT compared with straight urea in Irish grasslands. However, NBPT has been found to cause toxicity crops. Artola *et al.* (2011) reported chlorosis or yellowing of leaf tips, changes in amino acids composition and alteration in plant metabolic rate causing higher levels of urea in plant tissue in wheat (*Triticum aestivum* L.). However, these effects were suggested to be transitory. Watson & Miller (1996) observed leaf scorch or tip necrosis in perennial ryegrass 7 to 10 days following NBPT and urea application, along with reduced urease activity in shoots. Again, effects were transitory, while reduced nitrogen loss though ammonia volatilisation from NBPT application is suggested to lead to improved dry matter production and far outweigh initial negative impacts (Watson &

Miller, 1996). There are concerns over the potential fate of NBPT and that it may remain present in food products such as milk. Issues were noted with a nitrogen inhibitor called dicyandiamide (DCD) as fully outlined by Teagasc. Further information can be found at; https://www.teagasc.ie/publications/2019/protected-urea.php.

However, it is understood that concerns over NBPT are anecdotal, that the potential for residues to be present in food products is unlikely and that there is no current evidence of this occurring. A four- year project has commenced under Teagasc to examine the fate of NBPT, including the likelihood of its entry into food chains. Finally, it must also be noted that the application of urea leads to carbon dioxide emissions. In 2017 this accounted for roughly 0.2% of agricultural emissions (Duffy *et al.,* 2019).

Despite no significant difference observed between CAN and urea for Spring cereal systems (Roche *et al.,* 2016), Harty *et al.* (2016) reported less nitrous oxide emissions on grasslands with the use of urea compared with CAN, estimated a reduction potential of 70% in nitrous oxide emissions by substituting CAN with urea and suggested urea treated with NBPT, could reduce overall fertiliser costs. Additionally, Forrestal *et al.* (2017) found no significant difference in annual grass yields between the use of CAN and urea, though noted a slight decrease in efficiency of between 4 and 8% associated with urea through loss of nitrogen by conversion to ammonia. None the less, the substitution of CAN with protected urea is seen as a viable option, with urea protected with NBPT currently costing roughly the same as CAN (Lanigan *et al.,* 2018). Additionally, refined or Tier 2 emission factors for Ireland (Harty *et al.,* 2016; Roche *et al.,* 2016) for use in inventory calculations, will aid more accurate national accounting.

Nitrogen fertiliser replacement by multi-species swards

The application of inorganic nitrogen fertilisers in Ireland was estimated to account for 38% of national nitrous oxide emissions (Lanigan *et al.,* 2018). Roughly half the amount of nitrogen applied to soils is used by growing crops, with the remainder open to loss through multiple processes including denitrification (Watson *et al.,* 2009). The most effective means of reducing impacts of fertilisers is to reduce the amount applied, which is also easily quantified for national inventory purposes. The use of multi-species grass swards is a means of reducing artificial nitrogen inputs (Schils *et al.,* 2013), as the inclusion of legumes, typically clover (*Trifolium* L.) allows natural nitrogen fixation. Indeed, the use of clover has successfully formed a principle component of organic farming systems for years (Lampkin, 1990) and is identified as a measure within both the Teagasc (Lanigan *et al.,* 2018) and United Kingdom (Eory *et al.,* 2015) MACCs.

Research in Switzerland demonstrated legume-grass swards fertilized with 50 kg N ha^{-1} yr^{-1} gave the roughly the same yield as a grass monocultures that received 450 kg N ha^{-1} yr^{-1} (Nyfeler *et al.,* 2009). Legumes in general can produce up to 400 kg N ha^{-1} yr^{-1} though this rarely occurs in agricultural pastures, with average nitrogen fixation in temperate, grassed pastures estimated to be between 80 and 100 kg N ha^{-1} yr^{-1} (Ledgard, 2001). Research in Ireland (SmartGrass Project) showed a reduction in direct nitrous oxide emissions from nitrogen fertiliser of 19 g N_2O-N t DM^{-1} ha^{-1} yr^{-1} associated with grass-clover swards compared to monoculture grass swards, with both swards receiving 90 kg N fertiliser ha^{-1} yr^{-1} (Murphy *et al.,* 2018). The SmartGrass project also indicated that grass-clover swards receiving between 40 and 90 kg N ha^{-1} yr^{-1} will generate comparable yields to monoculture ryegrass swards receiving intensive nitrogen fertilisation (≈ 250 kg N ha^{-1} yr^{-1}).

Species rich swards, which may include herbs such as chicory (*Cichorium intybus* L.) and plantain (*Plantago lanceolota* L.) in addition to clover, have potential co-benefits, such as reduced nitrogen leaching (Romero *et al.,* 2017) anthelmtic properties, therefore enhancing livestock health (Lüscher *et al.,* 2014; Grace *et al.,* 2018) and improved drought resistance (Sanderson *et al.,* 2005), the latter important for climate change adaptation. Additionally, the nutritional value and digestability of grass and forage may be enhanced (Lüscher *et al.,* 2014). Total nitrogen within swards was found to be significantly greater in legume-grass mixes compared to grass monocultures at sites across Europe with mixtures containing a third clover, obtaining optimal total sward nitrogen and 57% more than grass monocultures (Suter *et al.,* 2015). Nitrogen fixation by clover is regulated by the soil nitrogen sink (Suter *et al.,* 2015) and can be negatively affected by the use of fertiliser (Nyfeler *et al.,* 2009). However relatively low nitrogen application rates are unlikely to discouraged clover. The majority of farmland surveyed across a three regions in Ireland was classified as intensive or improved grasslands respectively (Sheridan *et al.,* 2017). Despite some clover being present in swards, the former consist predominantly (≥ 70%) of perennial (*Lolium perenne*) or Italian rygrass (*Lolium multiflorum*) while the later are dominated (< 70%) by perennial ryegrass. Clearly there is considerable opportunity to increase the area of multi-species swards.

Soil fertility management

Increasing nitrogen use efficiency and therefore negating the need for fertiliser application by optimizing soil pH is deemed an important mitigation measure in MACCs for both the United Kingdom (Eory *et al.,* 2015) and Ireland (Lanigan *et al.,* 2018). LCA analysis indicated that nitrogen use efficiency is key factor in reducing the carbon footprint of milk production in Ireland (O'Brien *et al.,* 2014). Theoretically, if soil pH is sub-optimal, greater quantities of nitrogen fertiliser is required to offset reduced soil nutrient cycling to maintain plant performance and ultimately, crop yields. The benefits of applying lime to manipulate soil pH are well recognised (Holland *et al.,* 2018). Soil pH, a measure of the concentrations of hydrogen ions (H^+) considerably effects nutrient availability by influencing mineralisation or the breakdown of organic matter by both soil macro- and micro-organisms (Parkinson, 2003). Kemmitt *et al.* (2006) observed a significant positive correlation between soil pH with not only, crop productivity and microbial respiration but, nitrification, soil microbial biomass carbon and nitrogen.

In Ireland, lime applications are and have been historically considered crucial for agricultural activity. Irish soils are prone to acidity from leaching associated with high precipitation levels (Collins *et al.,* 2004). However, liming using limestone or calcium carbonate (CaCO3) to correct soil pH, generates carbon dioxide. In Ireland, emissions from liming were estimated to be 332.7 kt CO_2, accounting for 1.7% of total agricultural emissions in 2017 (Duffy *et al.,* 2019). It is also worth noting that, as improving soil pH leads to increase microbial activity and therefore nutrient turn-over, a potential increase in carbon breakdown and emissions may occur (Moxely *et al.,* 2014). However, Paradelo *et al. (*2015) found that this is only temporary and offset by higher plant productivity, which generates greater carbon returns to the soil. Liming may also alter soil structure by enhancing clay particle bonds and aggregation, thereby providing greater protection to soil organic carbon (Paradelo *et al.,* 2015). Of course liming will impact all soil nutrient availability, including trace elements. Holland *et al.* (2015) outline how liming will impact both potassium (K) and phosphorus (P) levels, potentially leading to both increases and reductions in availability. Potassium, depending on the soil cation exchange capacity, is normally readily available and formed from the weathering of parent material and clay (Parkinson, 2003). Parkinson (2003) also noted how high levels of hydrogen ions associated with low pH, flood the cation exchange system and restricts potassium availability. Climate is recognised as responsible for low levels of potassium in Irish soils, with leaching a result of precipitation exceeding evapotranspiration (Collins *et al.,* 2004). Phosphorus is derived from the weathering of parent material, though this process is extremely slow, with mineral forms also be held in soil organic matter (Parkinson, 2003). According to Collins *et al.* (2004) mineralisation of organic matter, a biological process therefore dependant on factors including soil pH, may account for 30 to 70% of available phosphorous.

Currently in Ireland there is considerable concern about soil fertility. Teagasc estimated that 88% of grassland soils have sub-optimal pH, phosphorous or potassium levels with only 12% considered to have optimal soil fertility (Plunkett, 2018). Considering potassium and phosphorous, Plunkett (2018) also outlined that 61 and 64% of grassland soils exhibit suboptimal optimal levels respectively. The correction of potassium and phosphorous in conjunction with soil pH is deemed important to optimise to the soil system performance and negate the need for compensatory nitrogen inputs to maintain production.

Low emission slurry spreading

As previously discussed, there is urgent need to reduce ammonia emissions in tandem with greenhouse gas emissions in Ireland (EPA, 2018d). A survey conducted in 2011, indicated that the majority (97%) of farms surveys spread slurry using splashplate systems (Hennessy *et al.,* 2011). The use of trailing shoe, shallow injection and band spreading application equipment were found to reduce ammonia emission by 57%, 73% and 26% respectively compared to splashplate type broadcasting (Misselbrook *et al.,* 2002). A review conducted by Webb *et al*. (2010) identified trailing shoe and open injection as most efficient compared with a trailing hose, with potentially less variation associated with trailing shoe application. The exposure of slurry to ambient air causes volatilisation and an associated release of ammonia. Methods that ensure the direct delivery of slurry either into the ground or sward limit the opportunity for volatilisation. Misselbrook *et al*. (2002) noted a significant (P = < 0.05) trend between increasing sward height and decreasing ammonia emissions, highlighting the effects of cover, following slurry deposition. Similarly, ploughing and therefore incorporating slurry immediately after application on arable soils, may also reduce emissions (Webb *et al.,* 2010)

However reduced volatilisation enhances the level of available nitrogen and therefore may lead to increased nitrous oxide emissions. Indeed, nitrous oxide and ammonia emission fluxes may be antagonistic and trailing shoe application techniques have been associated with increased direct nitrous oxide emissions. Bourdin *et al.* (2014) indicated that though trailing shoe led to reduced ammonia volatilisation and indirect nitrous oxide emissions compared to splash plate applications, an increase in direct nitrous oxide emissions may offset any benefits. It was suggested that the timing of application was important, with Spring applications generating less ammonia and greenhouse gas emissions as a result of soil and climatic condition favouring crop growth. Drier conditions are generally associated with higher ammonia volatilization, carbon dioxide fluxes and lower nitrous oxide fluxes, with nitrous oxide directly linked to soil water-filled pore pace (Louro *et al.,* 2013). Webb *et al*. (2010) suggested increased nitrous oxide emissions associated with ammonia emission reduction techniques are not inevitable, with rapid incorporation of slurry identified as beneficial. Overall, low emission slurry spreading techniques were identified in the Teagasc greenhouse gas MACC analysis as an effective mitigation measure (Lanigan *et al.,* 2018).

Low emission technology is expensive though grant aid for up to 40% of costs to a maximum of €40,000 through TAMS II under the Low Emissions Slurry Spreading (LESS) Scheme (DAFM, 2018d), is available for farmers to purchase equipment.

Soil structure management and drainage of mineral soils

Soil structure describes the product of soil particles being bound together to form units known as aggregates and the resulting spaces or void within or between the aggregates known as pores (Russell, 1973; Ghildyal & Tripathi, 1987; Kay, 1990). Soil structure is suggested to underpin soil quality as it influence soil physical, chemical and biological characteristic (Mueller *et al.,* 2013), These include soil hydrology, aeration, soil temperature, therefore soil microbial activity, nutrient availability, solute transport, gaseous exchange and root growth (Roger-Estrade *et al.,* 2009). Therefore soil structure influences greenhouse gas emissions. Ball *et al.* (1999) outlined the impacts of changes in soil structure caused by tillage on carbon dioxide, nitrous oxide and methane emissions. Nitrous oxide and carbon dioxide fluxes were determined by air-filled porosity and gas diffusivity. Ploughing, which helps alleviate compaction and aerate the soil, was suggested to reduce nitrous oxide emissions while methane oxidation was described as being effected by long-term compaction. Nitrous oxide fluxes were found to be greatest on compacted soils following fertilisation and rainfall (Ball *et al.,* 1999). Indeed, soil compaction is recognised as an important driver of nitrous oxide emissions (Schmeer *et al.,* 2014).

Soil compaction describes a reduction in volume of a certain mass of soil, therefore altering soil porosity, as a result of applied pressure (McKibben, 1971; Marshall *et al.,* 1996). Compaction can result from both machinery operations and livestock traffic (Bilotta *et al.,* 2007; Batey, 2009). Processes such as pugging (indentations caused by livestock hooves) and poaching (the rendering of soil conditions to a soup-like state) result from livestock treading (Drewry, 2006) and are notable problems in wet soil conditions (Hamza & Anderson, 2005) when soils are weak and prone to damage (Batey *et al.,* 2009; Ball *et al.,* 2012). Induced livestock trampling was observed to considerably increased nitrous oxide emissions from applied urine-N by (Ball *et al.,* 2012) while anoxic zones created within hoof indentations were found to lead to nitrogen losses by denitrification (Batey & Killham, 1986).

Soil structural degradation through processes such as compaction is of particular concern in temperate climates, due to persistently wet soil conditions (Creamer *et al.,* 2010; Newell-Price *et al.,* 2013). Every effort should be made to avoid compaction through the careful timing of machinery operations and livestock grazing (Creamer *et al.,* 2010). The prevention of soil compaction is indirectly identified within Irish MACC under grassland management for carbon sequestration (Lanigan *et al.,* 2018) but forms a specific measure for the United Kingdom (Eory *et al.,* 2015). As mentioned, there is potential conflict between extending the grazing season and preventing soil compaction. Trees planted within grassland may have the potential to help strengthen soil structure stability and resilience, capture nutrients not utilised by grass and therefore help to extend the grazing system (McAdam *et al.,* 2006).

With regards to soil drainage, roughly 60% of Irish agricultural soils were estimated to exhibit problems associated with wetness (Collins & Cummins, 1996). Issues associated with soil moisture and greenhouse gas emissions have been discussed, notably regarding nitrous oxide, where reduced aeration and water logging enhance nitrous oxide production. Improved soil drainage may reduce nitrous oxide emissions, while also potentially facilitating an extended grazing season. The drainage of wet mineral soils was identified within the Teagasc MACC analysis as a mitigation option, with the proposed use of gravel and shallow mole drains as well as deep drains in conjunction with subsoiling (Lanigan *et al.* 2018). Tuohy *et al.* (2016a) explored the efficiency of different mole systems on clay loam soils, with gravel mole drainage found to be preferable. However, the need for careful consideration of site-specific factors when designing and installing drainage systems was emphasised (Tuohy *et al.,* 2016b).

Regarding potential soil organic carbon losses by drainage of mineral soils, research by Kumar *et al.* (2013) suggests losses may occur. However this work was conducted on arable soils in the USA under maize (*Zea mays* L.) in conjunction with different tillage practices. The extent to which drainage of temperate mineral grasslands will lead to reduced soil organic carbon stocks is unclear. O'Sullivan *et al.* (2015) highlighted conflict between the production function, facilitated by land drainage on imperfectly-drained soils, and carbon storage in Ireland, suggesting drainage reduces carbon storage potential in certain scenarios. Nachimuthu & Hulugalle (2016) discussed the loss of dissolved organic carbon by deep drainage through the soil profile and highlighted a lack of associated data. However, improved soil functioning in terms of crop productivity and microbial activity, through improved drainage, may theoretically lead to greater carbon inputs and potentially accumulation.

A.2.2. CARBON STOCKS AND SEQUESTRATION POTENTIAL IN SOILS AND BIOMASS

A.2.2.1. Carbon sequestration in grasslands

A study of 14 managed grasslands across central Europe indicated that grasslands were generally a sink of carbon and a source of nitrous oxide with mixed trends noted concerning methane. Despite this, only one site of a subset of nine sites demonstrated a positive net greenhouse gas balance (emissions exceeded sequestration) and was associated with ploughing and reseeding (Hörtnagl *et al.,* 2018). The soil pool is the principle store of carbon within grasslands (as opposed to standing biomass) with soil organic carbon derived from inputs of dead vegetative material (grass) or if grazed, animal excreta. Irish grasslands provide second largest stock of soil carbon after wetlands (Eaton *et al.,* 2008). As mentioned, a review undertaken by the Royal Irish Academy highlighted the potential for grassland soils to further sequester carbon in Ireland but noted issues with the measurement, reporting and verification required for IPCC inventories (RIA, 2016). Xu *et al.* (2011) estimated national soil organic carbon stocks to be 383 (± 38) and 1,475 (± 181) Tg within 0 to 10 and 0 to 50 cm soil depths respectively, of which grasslands represented roughly 53%. Total grassland soil organic carbon stocks were estimated to be 203 (± 35) and 769 (± 163) Tg for 0 to 10 and 0 to 50 depths respectively. In terms of density, this equated to 55 (± 11) t SOC ha^{-1} within 10 cm depth, or 207 (± 49) t SOC ha^{-1} within 50 cm depth. At field scale, Keily *et al.* (2009) observed mean soil organic carbon contents of 6.6% at 0 to 10 cm depth a grassland site in Cork while carbon fractionation at eight sites in Southern Ireland indicated that the majority of soil organic carbon held within grasslands is relatively stable. Roughly 50% was classified as within the passive pool, contained within sand, stable aggregates and non-recalcitrant carbon contained with silt and clay. The remaining 50% was composed of carbon held within microbial and particulate organic matter (the active pool ≈ 25%) and recalcitrant forms of carbon held in silt and clay particles (the slow pool ≈ 25%). However, Jones *et al.* (2017) highlighted that that the carbon sink function of grasslands is not perpetual and grassland management should aim to limit carbon losses as much as increasing the quantity of carbon stored.

The rate of carbon sequestration in grassland soils can be twice that of arable soils (Kayser *at al.,* 2018). Jones & Donnelly (2004) outlined factors determining the rate of carbon sequestration in temperate grasslands including the input rate of material (organic matter), how quickly the material is broken down, the soil depth to which deposition takes place and the physical protection offered to organic matter within the soil matrix (e.g. within aggregates). Management greatly impacts soil organic carbon contents, with soil disturbance associated with carbon losses (Jones & Donnelly, 2004; Rumpel *et al.*, 2015; Conant *et al.,* 2017). For example, the conversion of grassland to arable production, significantly reduces soil organic carbon content (Soussana *et al.,* 2004). Teagasc recommended that leys or temporary grasslands should remain for at least five years before ploughing (Lanigan *et al.,* 2018). Indeed, the disturbance of established pasture to improve swards by reseeding, though agronomically beneficial, is likely to cause soil carbon losses (Kayser *et al.,* 2018). Considering grassland management, a review of international literature indicated that the inclusion of legumes, fertilization, improved grass-species and grazing management lead to increased soil organic carbon (Conant *et al.,* 2017). In general, practices that encourage pasture growth or enhance production, may lead to increased carbon sequestration (Jones & Donnelly, 2004).

Fertilization may affect sward and associated root growth, sward and therefore litter composition and in turn the metabolism of the microbial community, all impacting soil organic carbon stocks (Poeplau *et al.,* 2018). Rumpel *et al.* (2015) discussed the impact of sward nutrient status. The organic matter generated from an extensively managed sward, where little fertilization has occurred or where grass is allowed to mature, will be broken down slowly within the soil, remain in unstable forms for longer and therefore open to losses. Under an intensively managed system, the sward is likely to have a higher nitrogen content, be composed of leafy material and the associated organic matter will be rapidly broken down and locked-up within stable organ-mineral soil complexes more rapidly. Poeplau *et al.* (2018) found fertilization had a positive effect on soil organic carbon within upper 30 cm soil depth and found 1.15 kg nitrogen (contained within NPK fertiliser) correlated with a 1 kg carbon sequestered. However, the carbon footprint of the fertilisers required to enhance carbon sequestration must be considered. In terms of organic manures, Jones *et al.* (2006) observed mixed results with the application of manures to a Scottish grassland, where increases in carbon sequestration was offset by increased nitrous oxide emissions with variation between different manures types. However, regular application of organic manure to grasslands is likely to increase carbon sequestration and it was suggested that nitrous oxide emissions may be limited if manures are applied when grass growth requires increased nitrogen (Jones *et al.* 2006).

Equally, dung and urine deposition from grazing livestock may provide an important carbon input (Rumpel *et al.,* 2015).

In terms of grazing intensity on soil organic carbon, research in Canada found that moderate grazing increased soil organic carbon content by 12% within the upper 15 cm soil depth compared to no grazing, though also highlighted regional climatic variation and outlined mixed results reported by other studies (Hewins *et al.* 2018). Indeed, Abdalla *et al.* (2018) also noted regional impacts of grazing and suggested that in cool moist zones, which included temperate climates, reductions in soil organic carbon are associated with grazing. A meta-analysis conducted by McSherry & Ritchie (2013) indicated variability, region specific impacts and that increased grazing intensity of C_3 dominated grasslands (as found in temperate climates) may negatively impact soil organic carbon. A review conducted in the United Kingdom suggested that soil organic carbon may increase with moderate grazing though higher stocking density may negatively impact grass production and therefore soil organic carbon (Moxley *et al.,* 2014). Adaptive multi-paddock (AMP) grazing, a system emerging in the USA, involves grazing for short periods of time at high sticking density while facilitating plant recovery, promoting plant communities and soil protection. Evidence suggests that AMP systems may lead to higher carbon sequestration compared to continuous grazing (Stanley *et al.,* 2018). It appears an optimal “moderate” grazing intensity exists, below and above which soil organic carbon stocks may be depleted. Data specifically concerning temperate grasslands appears limited while short term experiments may not be sufficient to capture associated changes in soil organic carbon (EIP-AGRI, 2017). Work under the European Commission funded “Grass for Carbon” focus group (EIP-AGRI, 2017) as well as the Irish Government funded AGRI-SOC project (DAFM, no date) may provide useful insights.

It is worth noting that apart from enhanced nitrogen fixation by clover, multispecies swards containing herbs, may theoretically sequester more carbon due to greater rooting depths obtained. This was examined in Ireland as part for the SmartGrass Project and results are to be published shortly. However, gains in sequestration from sward composition modification, such as the inclusion of herbs, will be relatively minor compared to gains from complete land use change, for example the conversion of arable to grassland system.

A.2.2.2. Forests and woodland

Afforestation

The mitigation potential of forestry is widely recognised including in Ireland (DAFM, 2015c; 2015d). The national Climate Mitigation Plan suggests Irish forestry and the use of associated products could potential sequester 20 to 22% of agricultural emissions annually (DCCAE, 2017). Irish forestry is estimated to currently represent a sink of 312 Mt C, while removing 3.8 Mt CO_2-eq annually between 2007 and 2016 (DAFM, 2018a). The latter estimate does not include associated emissions including forest fires, drainage of organic soil under forestry or fertiliser use. The CARBWARE model (Black, 2016), used to estimate national carbon stock changes, includes these factors and estimated net emissions from forested land to be - 3,728.1 kt CO_2-eq (carbon dioxide = - 4,013.7, methane = 104.8, and nitrous oxide =180.8 kt CO_2-eq) in 2017 (Duffy *et al.,* 2019).

In order to achieve the National Forest Policy Objective of 18% forest cover by 2046, an afforestation rate of 15,000 ha yr^{-1} was identified as required (DAFM, 2014). Current annual rates may be as low as 4,000 ha yr^{-1}. This shortfall in combination with the legacy of a large area historic afforestation reaching harvestable status means a decline in the annual forestry carbon sink is likely to occur from 2025 onwards.

It must be noted that deforestation also occurs in Ireland (Duffy *et al.,* 2019), with 6,432 hectares reconverted from forestry between 2006 and 2017 from factors including deforestation (DAFM, 2018a). Grants currently available for the conversion of agricultural land under the afforestation scheme (DAFM, 2015d), includes 12 measures (GPCs) ranging from establishment of Sitka spruce (*Picea sitchensis* L.) or Lodgepole pine (Pinus *contorta* L.) stands (GPC 2) to deciduous native woodland (GPCs 9 & 10) or trees for fibre production (GPC 12). As discussed, agroforestry is also supported (GPC 11). GPC measures are designed to cover the cost of establishment. Additional premia are provided on the establishment of new forests and payable for 15 years. Separate schemes are available to support aspects such as forestry roadway construction, thinning broadleaves or native woodland conservation. Grants and premia require the re-classification of agricultural land to forest land however, land afforested since 2009 is still eligible for Basic Farm Payment Scheme and premia are exempt from income tax.

Despite grants and premia, there are considerable barriers to afforestation and may limit the contribution that forestry will make to mitigation. Apart from geophysical constraints, lack of adequate financial incentive or familiarity with forestry along with negative perceptions may discourage farmers from entry into schemes (Farelly & Gallagher, 2015; Ryan & O'Donoghue, 2016; Ryan *et al.,* 2018). Farmers' awareness regarding afforestation has been discussed (Section 3.4.1.). Ryan and O'Donoghue (2016) suggested a number of policy recommendations including: the full recognition and proportional reward for the public service that farmers provide by planting trees, the option for guaranteed Government advanced purchase of timber before maturity, government forestry insurance schemes, the combining of land use options, linking carbon neutrality with agricultural activity, improved extension, funds for planting subsequent rotations, provision for land reversion to agricultural land and greater certainty on impacts of afforestation on payment schemes. Ryan *et al.* (2018), additionally identify the mutually exclusive relationship between agriculture and forestry policy as a barrier to afforestation.

In conjunction to attitudinal barriers, Farrelly & Gallagher (2015) highlighted potential conflict over land use. An assessment of the land available for afforestation indicated that, of the 4.65 million hectares technically, suitable for afforestation, 896,880 hectares is designated as habitat conservation areas while 2.42 million hectares are under productive agriculture. The remaining available land (1.3 million hectares) is considered marginal agricultural land, (Farrelly & Gallagher, 2015) wet grasslands and various non-intact or modified peatland types, issues with which are discussed later. This highlights issue of the availability of land to accommodate multiple and sometime competing, functions (Schulte *et al.,* 2014), whether agriculture, forestry or biodiversity conservation in this case. To maximise sequestration in the medium term, conifer stands on mineral soils are favoured. However, this is undesirable from biodiversity, water quality and other multifunctional land provision perspectives. The importance of diversity within afforestation has been highlighted (Seddon *et al.,* 2019). Management at a landscape level may therefore be important to ensure multifunctionality, with the designation of areas for different function including, optimal carbon sequestration by forestry.

Carbon sequestration by Agroforestry

Agroforestry, widely noted for both climate change mitigation (Aertsens *et al.,* 2013; Lorenz & Lal, 2014; De Stefano & Jacobson, 2018) and adaptation (Verchot *et al.,* 2007; Mbow *et al.,* 2014; Hernández-Morcillo *et al.,* 2018) potential, is defined as the integration of cultivated woody perennials (e.g. trees) within either livestock or crop production systems on the same unit of land, bringing associated ecological and economic interactions (Nair, 1993). A variety of agroforestry systems exist (Feliciano *et al.,* 2018) with notable adoption in tropical climates (De Stafans & Jacobson, 2018; Feliciano *et al.,* 2018), though identified as a mitigation action for Europe (RICARDO-AEA, 2016). Silvopastoralism refers to the integration of trees within grazed grassland or pastoral systems. Due to the proportion of grassland (EPA, 2016), there is significant opportunity for silvopastoralism in Ireland (McAdam *et al.,* 2006; McAdam & McEvoy, 2009).

Though caution in accounting is required (Nair, 2012) and a scarcity of data exists (Lorenz & Lal, 2014; Feliciano *et al.,* 2018) notably for temperate climates (Eory *et al.,* 2015), agroforestry is generally associated with increase carbon accumulation in terms of both below ground soil stocks and within the above ground, standing biomass (Jose & Bordhan, 2012; Feliciano *et al.,* 2018). Tree roots allow the accumulation of carbon within deeper soil horizons (Lorenz & Lal, 2014). Recent meta-analyses found agroforestry generally lead to greater soil organic carbon compared to agriculture in multiple regions (De Stafans & Jacobson, 2018; Chatterjee *et al.,* 2018) except in temperate climates (Chatterjee *et al.,* 2018). Indeed higher rates of sequestration were observed in tropical regions (Feliciano *et al.,* 2018). Considering silvopastoral systems only, Feliciano *et al.* (2018) report sequestration by above ground biomass of between 0.15 t C ha^{-1} yr^{-1} in Africa, to 2.65 t C ha^{-1} yr^{-1} in Asia. Below ground soil carbon sequestration ranged from 0.06 t C ha^{-1} yr^{-1} in North America to 6.54 t C ha^{-1} yr^{-1} in Latin America, with the greatest mean absolute change for all regions, associated with conversion of grassland to silvopastoralism (+ 4.4 t C ha^{-1} yr^{-1}). Regarding methane and nitrous oxide net emissions, Kim *et al.* (2016) found areas under agroforestry were roughly the same as adjacent agricultural land.

Considering Europe, agroforestry legislation (EU Regulation 1698/2005) was introduced to encourage agroforestry (de Jalón *et al.,* 2018) with rates of sequestration from implementation on both arable land and pasture were estimated as roughly 10 t CO_2-eq ha^{-1} yr^{-1} (Aertsens *et al.* 2013). Roughly 15.4 million hectares are currently under agroforestry across the Europe Union (de Herder *et al.,* 2017) with adoption was found to be determined by multiple positive and negative perceptions, the latter associated with increased labour, management costs and administration (de Jalón *et al.,* 2018). None the less, an assessment of European agroforestry with the goal of its promotion for rural development (AGFORWARD Project) was recently completed and highlighted the interest in, and the potential of such systems (Burgess *et al.,* 2018). It is worth noting that livestock agroforestry forms the most prominent system (15.1 million hectares) within the European Union (de Herder *et al.,* 2017). Agroforestry in temperate regions within arable systems was found to enhance soil conditions in terms of soil organic carbon content and nutrient concentrations attributed to leaf litter (Pardon *et al.,* 2017). For grasslands, agroforestry is identified as a strategy for sustainable land management in Northern Ireland (DAERA, 2018) with research conducted at Agri-food and Biosystems Institute (AFBI) Loughgall, Co. Armagh. Ash (*Fraxinus excelsior* L.) were planted 5 m apart or 400 trees ha^{-1} which allowed successful grazing of sheep. Indeed, careful considerations of factors such as tree inter- and intra-row spacing, row orientation and likely agricultural field operations is required (de Jalón *et al.,* 2018). However, agricultural operations can successfully continue.

To allow trees to fully establish, grazing by sheep is recommended for up to seven years, after which cattle can be introduced (DAERA, 2018). Though empirical research in the Republic of Ireland is limited, Short *et al.* (2005) showed successful grazing of cattle between oak (*Qeurcus robur* L.) during an experiment at Johnstown Castle, Co. Wexford. Trees were planted in rows with 0.75 m intra-row and 2 m inter-row spacing (6,600 tress ha^{-1}). Regrettably, carbon sequestration was not measured. The research in Northern Ireland demonstrated no significantly difference in soil carbon storage between 26 years of silvopasture and permanent pasture. However, greater quantities of carbon were observed in the micro-aggregate (53 to 250 μm) and the silt and clay fractions (< 53 um) in soils under a silvopastoral system. Greater macro-aggregate (> 2mm) carbon pools were found under grassland. Long-term storage of carbon is associated with that held in silt, clay and micro-aggregate fractions and it was concluded that silvopastoralism lead to more stable carbon pools that may have greater resilience to future climate change (Fornara *et al.,* 2017).

In addition to carbon sequestration, agroforestry may generate other benefits. Lorenz & Lal (2014) describe how the integration of trees in agricultural systems may positively alter the soil environment regarding hydrology, aeration, organic matter deposition, all effecting soil organisms including microbial communities. In an Irish context this may allow extended grazing seasons, as soils may have enhanced drainage and increased structural stability (DAERA, 2018). A significant issue concerning extended grazing is soil compaction (Harris, 1971) as a result of livestock treading (Drewry, 2006) associated with increased soil moisture content later in the year, making the soil more prone to structural degradation (Hamza & Anderson, 2005; Houlbrooke & Laurenson, 2013). The extension of the grazing season was identified as a measure to reduce livestock emissions (Lanigan *et al.,* 2018) as previously discussed. Deeper tree roots may also intercept un-utilised nutrients from the associated agricultural system (McAdam *et al.,* 2006), for example nitrogen that in turn, enhances tree growth, biomass accumulation and potential carbon sequestration capacity.

Depending on policy framework, agro-forestry gives flexibly with regard to land use allowing a form of forestry and agricultural activity, and deemed more attractive to farmers compared to afforestation, therefore potentially encouraging uptake. In Europe, lack of knowledge and financial support were identified as key barriers to agroforestry (Hernández-Morcillo *et al.,* 2018). Currently in Ireland, the only grant aid for the establishment of agroforestry (GPC 11) is part of the afforestation scheme (DAFM, 2015). Though farmers are still eligible for the Basic Payment Scheme (formally termed Single Farm Payment) under this scheme (DAFM, 2015), entry requires land to be permanently classified as forestry, which may discourage farmers (Farrelly & Gallagher, 2015; Ryan *et al.,* 2018). Despite these issues, a number of holdings have successfully adopted agroforestry with roughly 55 to 60 hectares estimated to be in, either planned conversion or established agroforestry in Ireland at present.

A.2.2.3. Carbon sequestration by hedgerows

Hedgerows are recognised as an important carbon sink and have mitigation potential if the area of hedgerow is increased (Falloon *et al.,* 2004; Black *et al.,* 2014). Carbon sequestration by hedgerows is associated with either storage within soils or above ground woody biomass (Thiel *et al.,* 2015). Research in Belgium indicated soil organic carbon to 20 cm soil depth was 8% higher at 1 m, compared to 30 m away from a hedgerow in an arable field (Van Vooren *et al.,* 2018) while a review of literature suggested soil carbon stocks within hedgerows were 22% higher than in arable land without hedgerows (Van Vooren *et al.,* 2017).

It is difficult to ascertain recent changes in levels due to reclassification of scrubland altering figures (DAFM, 2018a) though a decline of 4,548 hectares (1.6%) was noted between 2006 and 2012. An EPA report (Green *et al.,* 2016), estimates that nationally there is 689,000 km of hedgerow in Ireland (Green *et al.,* 2016). A survey of 118 farms over three regions, found on average, 13% of farmland area consisted of semi-natural habitat, the majority of which consisted of hedgerow (Sheridan *et al.,* 2017). Hedgerows were estimated to account for roughly 9% of area on farms. At a landscape level, Bourke *et al.* (2014) estimated a hedgerow density of 10.37 km per 1 km^2. It is worth noting that the area of semi-natural habitat on farmland in Ireland is higher than European averages (Sheridan *et al.,* 2017) with for example, natural habitat accounting for just 2.1% of farmland in the Netherlands (Manhoudt & de Snoo, 2003). This highlights the importance and potential contribution of semi-natural habitat and specifically hedgerows in Ireland. In terms of carbon sequestration, difficulties in terms robust accounting methodology and reporting to inventories were noted (Black *et al.,* 2018) with lack of monitoring data restricting analysis and inclusion (Duffy *et al.,* 2018).

With regard to current hedgerow condition, an in-depth assessment of 50 farms in South-Eastern Ireland, indicated that 49% of hedgerows were maintained as stock proof while there was no evidence of newly planted hedgerows observed on any of the farms surveyed (Sheridan *et al.,* 2011). When specifically examining intensive grassland farms (with stocking rates ≥ 1.5 Livestock Units ha^{-1}) semi-natural habitats accounted for 7.4% on average and hedgerows were again found to be the most abundant semi-natural habitat type (Larkin *et al.,* 2018). Of the 290 hedgerows surveyed on these farms, 129 (44.5%) were ranked as “significant” considering factors including species diversity, landscape importance and connectivity. The hedgerow condition score is a semi-quantitative assessment considering unfavourable categories such as basal density, invasive species and gappiness, with a maximum score of 24. A mean score of 12.05 was obtained with 85.5% of hedgerows exhibiting at least one unfavourable category. Hedgerow condition is known to be important for ecological reasons (Garratt *et al.,* 2017) but little research appears to have been conducted into management for optimal carbon sequestration. The planting of bio-diverse woody vegetation within a hedgerow was suggested to increase soil carbon pools (Thiel *et al.,* 2015). Theoretically, the encouragement of growth and rejuvenation should enhance sequestration potential, with basal thinning and the maturing of individual hedge trees and shrubs undesirable. Management intervention such regular cutting in the short term and coppicing or hedge-laying in the long term are suggested as likely to be beneficial.

In addition to potential carbon sequestration, hedgerow networks and associated microenvironments within agricultural landscapes provide ecological benefits. These include habitat provision, floral and faunal diversity, pest control, soil conservation, habitat linkage and physical protection (Forman & Baudry, 1984; Hannon & Sisk, 2009; Van Vooren *et al.* 2017; Garratt *et al.,* 2017). Hedgerows may also act as barriers to livestock disease endemics. Of the 689,000 km of hedgerow in Ireland, 15% and 26% are classified as “shared” and “internal farm” boundaries respectively (Green *et al.,* 2016) therefore dividing farm holdings. Livestock diseases may pose a greater risk with global warming (Purse *et al.,* 2005). Therefore, hedgerows may play an important role, not only in climate change mitigation, but also adaptation.

A.2.2.4. Carbon sequestration in organic soils

Organic soils under grassland

Renou-Wilson *et al.* (2014; 2018) loosely categorised organic soil grasslands as either occurring on is nutrient-rich or nutrient-poor. However, within these categories, the site-specific nature of emissions is emphasised. Renou-Wilson *et al.* (2014; 2015) identified not only nutrient status and drainage, but also grassland management as factors contributing to greenhouse gases. The average net ecosystem exchange over two years for grassland on a nutrient poor site with, shallow and deep drains was - 94 and - 56 g C m^{-2} yr^{-1} respectively (Co. Donegal). Mean annual methane emissions of 18 ± 15 kg CH_4 ha^{-1} yr^{-1} were observed at the shallow drained site. Considering the mean net ecosystem carbon balance, it was concluded that grasslands on nutrient-poor peats under extensive management with low nutrient inputs and where mean water table levels are maintained within 25 cm soil depth, have negligible impacts (Renou-Wilson *et al.*, 2015). It is recommended that agricultural activity, including grazing and fertiliser application, should cease and drains be allowed to naturally deteriorate, therefore restoring such sites to wetlands and enhancing their carbon sink function. Rushes (*Juncus effusus*) are likely to initially encroach. The control of rushes is required under current Cross Compliance regulation, with breaches impacting Basic Farm Payments. Therefore exceptions, under the circumstances of peatland restoration must be permitted.

In contrast to nutrient-poor sites, grasslands on nutrient-rich drained organic soils, which include fens, have considerable climatic impact (Renou-Wilson *et al.,* 2015). For example, Kroon *et al.* (2010) examined emission from a drained fen soil under grass in the Netherlands, supporting intensive dairy production. A final average greenhouse gases balance of 16 CO_2-eq Mg ha^{-1} yr^{-1} was observed, with carbon dioxide, nitrous oxide and methane accounting for 30, 45 and 25% respectively. It was concluded that this soil was considerable source of greenhouse gases (Kroon *et al.,* 2010). In Ireland emissions of 233 g C m^{-2} yr^{-1} and 0.16 g N_2O-N m^{-2} yr^{-1} were observed from a nutrient-rich grassland in Co. Longford (Renou-Wilson *et al.*, 2015). It was recommended that grasslands on nutrient-rich organic soil should be rewetted with consideration of specific site conditions.

Organic soils under forestry

Forestry occurs on organic and organo-mineral soils, accounting for 212,000 and 30,500 hectares respectively in 2016 (Duffy *et al.,* 2018). A decline in afforestation was observed on peats over the last 40 years though rates of afforestation on minerotrohic type peats has remained relatively constant (DAFM, 2018a). The disturbance and drainage of pristine or relatively intact peatlands for forestry is undesirable and should be avoided for reasons discussed. Despite afforestation of unenclosed or unimproved land being supported under GPD 1 of the afforestation scheme, planting on unmodified raised bogs, industrial cutaway peatlands or infertile blanket or raised bogs in the midlands, is forbidden within the scheme (DAFM, 2015). However, Coilte may still technically be able to plant blanket bogs, though it is assumed that this would not occur.

The afforestation of cutaway peatlands to meet national forestry targets was suggested and reviewed by Black *et al.* (2017). Renou-Wilson *et al.* (2008) had outlined Bord na Móna estimates of between 16,000 to 20,000 hectares as being potentially available, with research on cutaway peatland afforestation conducted under the BOGFOR project. Such forestry may be utilised for either biomass for energy generation or commercial timber production. However, issues were noted regarding the heterogeneity of excavated peatlands and not all sites are suitable. Specific sites such as gravity-drained fens are preferable with aeration, peat depth and nutrient status identified as limiting factors. Sitka spruce (*Picea sichencsis* L.) and Norway spruce (*Picea abis* L.) are suitable on shallow peats (≤ 1 m) while lodgepole pine (*Pinus contorta* L.), larch (*Larix* L.) and Scots pine (*Pinus sylvestris* L.) are more tolerant of deeper peats (< 2 m). Interestingly, birch (*Betula* L.) is tolerant of deeper peats, poorer drainage, and may facilitate Sitka spruce inter-planting (Black *et al.*, 2017). Black *et al.* (2017) also recommend that cutaway peatland afforestation decisions should be conduct at a landscape level to ensure the most appropriate land use (i.e. forestry, rewetting, grassland, short rotation coppice, amenity facilities) of different areas, all with consideration to biodiversity and arguably climate change mitigation.

The full impact of peatland afforestation from a climate change perspective is unclear as it is suggested that some of the carbon dioxide released may be absorbed by the growing tree biomass (DAHG, 2015). Net forest carbon balances consider multiple factors including above- and below-ground biomass, deadwood, litter and soil emissions (DAFM, 2018a). However, the carbon absorbed by trees represents short-lived capture and the longevity of its storage is dependent on the end use of the wood (Artz *et al.,* 2013). Wilson *et al.* (2013) suggest at a national scale, forestry on peatlands is a carbon sink, though raise issue with the aesthetic value, economics and carbon sequestration beyond the first rotation. The latter highlights the need to consider long-term impacts and whether the ecosystem represents a net carbon sink or source (Artz *et al.,* 2013). Considering the first rotation, Black & Gallagher (2010) modelled net greenhouse gases balances of forestry on blanket peat at different stages of development. Following initial drainage and planting (2 to 4 year), the site becomes a carbon source, emitting between 7 to 14 t C ha^{-1} yr^{-1}. Once trees are established and other vegetation colonises (4 to 8 years), the site becomes a carbon sink of between -2 to 3 t C ha^{-1} yr^{-1}. The site then remains a carbon sink, with maximum carbon uptake of - 12 to 30 t C ha^{-1} yr^{-1} before tree thinning (12 to 20 years). Renou-Wilson & Wilson (2018) suggested a lack of published data on emissions form forested peatlands while it must be remembered that carbon sequestered in peat is relatively stable. Intact and functioning peatlands represent a net carbon sequestering ecosystem in the long term, while long-term impacts afforestation are not clear (Artz *et al.,* 2013). Considering multiple rotations, afforested peatland ecosystems may represent carbon sources.

The impacts of rewetting existing forestry sites once clear-felled, as with other disturbed peatlands, is site specific. Following deforestation, it was recommended to block drains to raise the water table and maintain anaerobic conditions to prevent further peat decomposition (Black & Gallagher, 2010). More recent research showed that a rewetted forest site as a net source of carbon with emissions ranging from 1.02 to 5.60 t C ha^{-1} yr^{-1} (Renou-Wilson *et al.*, 2018). It was suggested that caution is required as brash left from forest harvesting may contribute to increased atmospheric and hydrological carbon dioxide emissions. None the less, rewetting, with proper management of the water tables and clear felled sites to accepted guidelines, is outlined as an option, but with prioritisation of peatland following other uses (Renou-Wilson *et al.*, 2018).

Cutaway and cutover peatlands

Cutaway (industrial) and cutover (domestic) peatlands (Wilson *et al.* 2013) are a substantial source of carbon dioxide with increased emissions associated with water table lowering and soil temperature increases (Renou-Wilson & Wilson, 2018). Since the 1920s, peat has been extracted as a source of fuel, with commercial extraction predominantly conducted by Bord na Móna (Duffy *et al.,* 2018), notably for electricity generation. Wilson *et al.* (2012) described the industrial peat extraction process, which initially requires the excavation of drainage channels to facilitate harvesting machinery. This lowers the water table, allowing carbon to be oxidised and causing the release of carbon dioxide. Following this, the removal of surface vegetation eliminates photosynthetic capacity and carbon capture, further shifting the carbon dioxide balance of the site, from being a sink to a source. Peat will then be extracted until exhausted, after which, there are a number of land use options including afforestation, agriculture or simply natural flooding or encroachment of scrub (Wilson *et al.* 2012).

In 2017, the area under industrial and domestic peat extraction was estimated to be 56,341 hectares (Duffy *et al.,* 2019). Bord na Móna aims to cease peat-fired electricity production by 2030 (Bord na Móna, 2018). The organisation implemented and is increasing the level of co-firing at their Edenderry power station (Co. Offaly) with ESB aiming to convert a further two power-stations to co-firing in 2019, with biomass supplementing peat in energy production (DCHG, 2017b). However, the provision of sufficient levels of biomass in Ireland to support co-firing is questionable, with recent sourcing of wood pellets from Africa (Bord na Móna, 2018). As Bord na Móna ceases peat extraction, significant areas of peatland will be available for alternative land use. Indeed, Wilson *et al.* (2012) estimated roughly 30,000 hectares.

The managed rewetting of former cutaway and cutover peatlands offers a considerable opportunity in preventing further carbon losses (Wilson *et al.* 2012; Renou-Wilson *et al.,* 2018), is recognised by IPCC accounting (IPCC, 2014b) and is identified in the National Peatlands Strategy as a potential option for climate change mitigation (DAHG, 2015). However, no specific actions regarding the rewetting of drained peatland were included within the strategy. Rewetting will either reduce carbon dioxide emissions, or at certain sites, generate carbon sequestration, though may increase methane emissions (Renou-Wilson & Wilson, 2018). Wilson *et al.* (2012) estimated that the rewetting of a former industrially extracted blanket bog at Bellacorick (Co. Mayo), reduced the global warming potential of the site by 87%, while mitigating 75 t CO_2-eq ha^{-1} over a six-year period. Restored surface vegetation was estimated to sequestered 279 ± 246 g C m^2 yr^{-1}. More recent monitoring of multiple sites as part of the NEROS project (Renou-Wilson *et al.*, 2018), indicated mean emission from drained nutrient-rich and nutrient-poor cutaway sites to be 1.51 and 0.91 t C ha^{-1} yr^{-1} respectively, while mean emissions of 1.37 t C ha^{-1} yr^{-1} were observed from a cutover site. Interestingly, a rewetted nutrient-rich cutaway site was a source with average emissions of 0.32 t C ha^{-1} yr^{-1}. The IPCC Tier 1 emission factor for rewetted nutrient-rich peatlands also indicated a positive value (IPCC, 2014b). Both rewetted nutrient-poor industrial cutaway and domestic cutover sites were sinks with average emissions of - 1.04 and - 0.49 t C ha^{-1} yr^{-1} respectively (Renou-Wilson *et al.*, 2018).

Rewetting is suggested to be a relatively cheap method of carbon dioxide avoidance and described as a “low-hanging fruit” for climate change mitigation (Wilson *et al.,* 2013). The emissions avoided over 50 years from rewetting ranged from between 100 and 151 t CO_2-eq ha^{-1} depending on site. Emphasis is on rewetting plans being in place before extraction ceases (Wilson *et al.,* 2012) and urgency regarding the commencement of the process, as if delayed the capacity for carbon storage and potential sequestration diminishes (Renou-Wison *et al.,* 2018). Peatlands that have only been drained and not excavated, should be prioritised for rewetting (Renou-Wilson *et al.,* 2018). Additional management of rewetted sites is required, to ensure that water tables remains sufficiently high. For example the removal of encroaching trees (e.g. birch or willow) may be necessary (Wilson *et al.,* 2012). Regarding co-benefits of rewetting and biodiversity, the re-establishment of bog flora on rewetted former industrial sites may be problematic, though achieved successfully on rewetted domestic cutover sites (Renou-Wilson *et al.,* 2019). In all cases, the need for proper, site-specific management is highlighted.

A.2.3. Avoiding carbon dioxide emissions through reduced fossil fuel use

A.2.3.1. Energy from biomass

Teagasc examined wood thinnings and sawmill reside for electricity and heat production, short rotation coppiced (SRC) willow (*Salix* spp.) and Miscanthus (typically *Miscanthus giganteus* L.) for heat generation, and SRC willow for electricity generation within the MACC (Lanigan *et al.* 2018). All of these measures had negative costs per tonne of CO_2-eq displaced.. It was suggested that SRC willow may contribute to a national requirement for 12% of heat generation by renewable sources by 2020. This is under the EU Renewable Energy Directive (EC, 2009). Willow will produce roughly 35 tonnes (moisture content = 25%) of biomass annually with 1.0 hectare potentially generating 172 GJ yr^{-1} at a moisture content of 20% (Caslin *et al.*, 2015a). Following three years of establishment, Miscanthus is suggested to give a yield of ≥ 10 t ha yr^{-1} (dry matter) (Caslin *et al.,* 2015b) with figures of up to 30 t ha yr^{-1} reported from research in Germany (Lewandowski & Heinz, 2003). Indeed, Miscanthus is generally considered as having the greatest potential as a biomass crop, due to high perennial yields and a relatively low greenhouse gas footprint (Arnoult *et al.,* 2015). However, it may be deemed less attractive in Ireland due to previous shortfalls or uncertainty within the market. Lack of demand may have been partly a result of Miscanthus ash clogging the furnaces grates currently used, due to the high potassium contents of the crop. Biomass ash contains high levels of potassium and calcium which together, reduce the melting point of ash, causing slagging or fouling of heat surfaces, while potassium and chloride emitted during combustion as potassium chloride (HCL) may cause corrosion (Lewandowski & Kicherer, 1997).

There is also uncertainty around uptake of Miscanthus as well as willow (Lanigan *et al.,* 2018). It is worth noting that agroforestry may contribute to the generation of biomass for either heat or electricity production (Jose & Bordhan, 2012), particularly as trees planted are not generally intended for commercial timber production. However, it is suggested that the use of biomass for energy production is suitable in the short term in pursuit of compliance with legislative targets, but this may undervalue biomass in the long term, with regard to its potential integration within the bio-economy.