An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030

Prepared by the Teagasc Greenhouse Gas Working Group

Gary J. Lanigan & Trevor Donnellan (eds.)

Authors:

Gary Lanigan, Trevor Donnellan, Kevin Hanrahan, Carsten Paul, Laurence Shalloo, Dominika Krol, Patrick Forrestal, Niall Farrelly, Donal O'Brien, Mary Ryan, Pat Murphy, Barry Caslin, John Spink, John Finnan, Andy Boland, John Upton, Karl Richards

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Agriculture and Food Development Authority

Executive Summary

- This is the second iteration of the Greenhouse Gas Marginal Abatement Cost Curve (GHG MACC) for Irish Agriculture to be published by Teagasc. This GHG MACC quantifies the opportunities for abatement of agricultural greenhouse gases, as well as the associated costs/benefits and visualises the abatement potential of GHG mitigation measures, and the relative costs associated with each of these measures.
- As such, the GHG MACC may be of use for guidance in the development of policies aimed at reducing greenhouse gas emissions from the non-Emission Trading Sectors (non-ETS). These are the sectors not subject to the Emissions Trading Scheme and, as such, fall under national competency (agriculture, waste, residential and transport sectors).
- This report has been prepared by the Teagasc Working Group on GHG Emissions, which brings together and integrates the extensive and diverse range of organisational expertise on agricultural greenhouse gases. The previous Teagasc GHG MACC was published in 2012 in response to both the EU Climate and Energy Package and related Effort Sharing Decision and in the context of the establishment of the Food Harvest 2020 production targets.
- Since publication of this previous GHG MACC analysis and the subsequent Carbon Neutrality Report, the context of discussions on agriculture and greenhouse gas emissions has continued to evolve.

Specifically, we have witnessed the following three developments:

1. The revised European Union Climate and Energy Framework and subsequent Effort Sharing Proposals (COM/2016/482) have changed the European policy environment on approaches to mitigating agricultural greenhouse gas emissions. Ireland has been proposed to reduce emissions by 30% relative to a baseline year of 2005, during the period 2021 to 2030. In addition, the inclusion of carbon (C) sequestration in the flexible mechanisms that can be used to achieve national targets mean that there is a wider suite of measures from which to achieve the required reductions.
2. At national level, the FoodWise 2025 Strategy has built on targets set in Food Harvest 2020.
3. Science and knowledge transfer (KT) activities in relation to agricultural greenhouse gas emissions have continued to evolve and are delivering further opportunities for a low-carbon agricultural sector. In addition, there have been advances in terms of beef genetics and manure management technologies over the last five years.

- In this current GHG MACC report, Teagasc quantifies the abatement potential of a range of mitigation measures, as well as their associated costs/benefits. The objective of this analysis is to provide clarity on the extent of GHG abatement that can realistically be delivered through cost-effective agricultural mitigation measures, as well as clarity on which mitigation measures are likely to be cost-prohibitive.

- The analysis in this report was conducted in the context of FoodWise 2025, an industry-led initiative that sets out a strategy for the medium-term development of

  the agri-food sector. The increase in agricultural output envisaged in FoodWise will provide a significant challenge to meeting emissions targets, particularly as agriculture comprises one-third of national emissions and 44% of the non-Emission Trading Sectors (non-ETS).
- The study assesses the additional potential for GHG abatement, C sequestration and the potential for the sector to displace fossil fuel consumption up to 2030, using a Baseline Scenario, generated by the FAPRI model, which projects agricultural activity to 2030. The mitigation identified in the GHG MACC then allows an assessment of the potential distance to any future sector specific GHG emission reduction target.
- This is not an exhaustive analysis of all GHG mitigation measures, but represents an assessment of best available techniques, based on scientific, peer-reviewed research carried out by Teagasc and associated national and international research partners.
- It is important to note that a MACC cannot be static or definitive: the potential for GHG abatement, as well as the associated costs/benefits are likely to change over time as on-going research programmes deliver new mitigation measures, or as socio- economic or agronomic conditions evolve. Therefore, the GHG MACC presented in this report should be interpreted as an addition to the previous analysis, that will in due course, be subject to further revisions as both scientific knowledge and socioeconomic conditions evolve.
- The analysis was approached differently for this iteration of the GHG MACC: the last version of the GHG MACC (Schulte et al., 2012) was based on the reductions associated with each measure. The total mitigation was then calculated as the cumulative sum of all measures. The current approach instead was based on inputting each measure into a model of the national GHG inventories for agriculture and land-use and land-use change. This approach enables any trade-offs between measures and their impact on individual gases to be assessed in a more holistic manner.
- Furthermore, the measures were sub-divided into three different categories:

  a) Agricultural Mitigation: Measures with reduced agricultural GHG emissions i.e. directly reduce methane (CH_4) and nitrous oxide (N_2O);
  b) Land Use Mitigation: Measures which enhance carbon dioxide (CO_2) removals from the atmosphere in terms of land management or Land-

Use, Land-Use Change and Forestry (LULUCF) and

c) Energy Mitigation: reductions from displacement of fossil fuels via energy saving, enhanced cultivation of biomass and/or adoption of anaerobic digestion.

- Furthermore, as the 2030 proposals are multi-year (i.e. from 2021-2030) and. higher or lower rates of uptake will impact significantly on the total amount of abatement achieved during this commitment period. In this study, linear uptake

  was assumed, although the impact of higher rates of uptake was included in a sensitivity analysis.
- Because of the multi-year proposals, we show the abatement potential in two ways: firstly as the mean abatement over the 10 year period (assuming linear uptake of the measure), and secondly as the maximum annual abatement level which occurs in the year 2030 when the measures are fully adopted. It should be noted that the headline target of a 30% reduction in Irish GHG emissions from the non-ETS sector relates to 2030 and thus the maximum annual abatement level is important to assess the contribution towards this target, whilst accepting that the target must be reached in a linear pattern.
- The analysis was broken down between a) agricultural emissions, b) land-use, land-use change, c) energy. This reflects Teagasc's four point approach to reducing GHG emissions:
  - o stabilise CH_4 emissions through increased efficiencies.
  - o de-couple N_2O emissions from production via nitrogen use efficiency and the use of low emission fertilisers and spreading techniques.
  - o absorb CO_2 via carbon sequestration in forests and soils while also reducing CO_2 emissions from hotspots (organic soils).
  - o fossil fuel displacement has the potential to offset fossil fuel emissions either by energy saving measures or substitution with bioenergy.
- In the absence of any mitigation, agricultural GHG emissions are projected to increase by 9% by 2030 relative to the 2005 baseline. This projected increase is mainly driven by increased dairy cow numbers and fertiliser use. However, the extent of any increase by 2030 is highly uncertain and may increase or decrease dependent on changes in total animal numbers and fertiliser inputs.
- Agricultural Mitigation: the total *mean abatement potential* arising from cost- beneficial, cost-neutral and cost-positive mitigation measures for *agricultural* emissions (CH_4 and N_2O), and assuming linear rates of uptake was 1.85 Mt of carbon dioxide equivalents (CO_2-e) per annum between 2021 and 2030, compared to the baseline scenario. The *maximum annual abatement* in the year 2030 was 3.06 Mt of carbon

dioxide equivalents (CO_2-e, Figure S1).

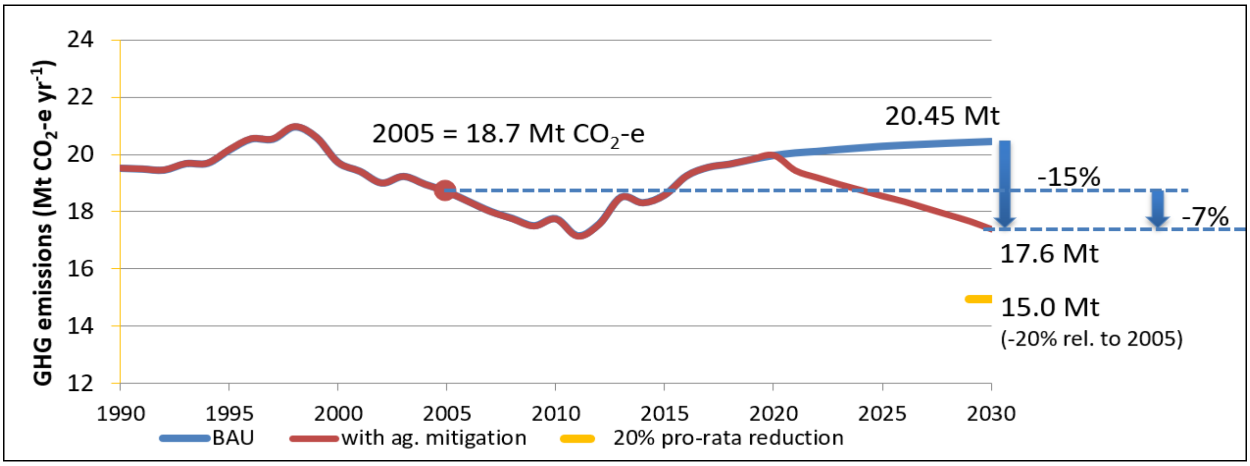


Figure S1: Agricultural GHG emissions from 1990 and projected to 2030, without (blue) and with (red) mitigation. The orange line represents a *pro-rata* 20% reduction in sectoral emissions by 2030.

- Land-Use Mitigation: The enhancement of CO2 removals could potentially remove another 2.97 Mt CO_2-e per annum on average from 2021-2030. The maximum annual removal in the year 2030 was 3.89 Mt of carbon dioxide equivalents (CO_2-e). However, under current flexibilities, sequestration would be capped at 2.68 Mt CO_2-e per annum.
- Energy Mitigation: The cultivation of biofuel/bioenergy crops along with adoption of anaerobic digestion and biomethane and on-farm energy saving has potential to account for a further reported reduction of 1.37 Mt of CO_2-e per annum from 2021-2030, mainly associated with the displacement of fossil fuel usage. The *maximum annual abatement* in the year 2030 was 2.03 Mt of carbon dioxide equivalents (CO_2-e). However, in the National Emissions Inventory, these reductions would largely be attributed to the fuel consuming sectors, i.e. the transport sector and power generation sector.
- The costs of these measures over the period under consideration (2021-2030) are highly variable as they are sensitive to uptake rate and other

associated externalities. The total level of abatement of all three categories averaged over the period 2021-2030 and assuming linear uptake of all measures was 6.19 Mt CO_2-e per annum. By the year 2030, *maximum level of uptake* should be achieved. These will equate to total mitigation of 8.99 MtCO_2-e comprised 3.06 Mt CO_2-e for agriculture, with further mitigation of 3.89 Mt CO_2-e and 2.03 Mt CO_2-e from the land-use and energy sectors respectively. The optimal carbon price, at which most mitigation could be achieved was assessed to be €50 per tonne CO_2e and these measures are listed in Table A below. This results in a total cost-effective mean mitigation value of 5.53 Mt CO_2-e yr^{-1} between 2021-2030

and a maximum cost-effective abatement value of 7.795Mt CO_2-e in 2030 (Table S1).

Table S1: Agricultural GHG emissions from 1990 and projected to 2030, and the cost effective abatement potential at a C price of €50/tonne.

	Actual emissions (Mt CO_2-e yr^{-1})			**Projected emissions or abatement under S1**	
	1990	2005	2016	Mean over 2012-2030 period	2030
Total Agricultural emissions (ex. Fuel)	19.51	18.69	19.24	20.28	20.45
Agricultural mitigation				1.73	2.89
Land-Use mitigation*				2.80	3.50
Energy mitigation				0.99	1.31
Total mitigation				**5.52**	**7.70**

*The LULUCF offsets are capped at a total of 26.8 MtCO_2-e for the period 2021-2030

- **It is important to note that these figures for all measures are highly dependent on uptake rate.** Realisation of these reductions will require a concerted effort from farmer stakeholders, advisory services, research institutes, policy stakeholders and the agri-food industry, and incentives may also be required, particularly in the case of both carbon sequestration and energy.

Glossary of Terms

Activity data	Data that quantify the scale of agricultural activities associated with greenhouse gases at a given moment in time. Activity data are expressed as absolute numbers (e.g. number of dairy cows, national fertiliser N usage) and typically change over time.
AD	Anaerobic Digestion
AFOLU	Agriculture, Forestry and Land-Use
Biophysical constraint	Limitation, set by the natural environment, which is difficult or impossible to overcome. Example: "the use of bandspreading equipment for slurry spreading in spring is biophysically constrained to well-drained and moderately-drained soils, and is excluded from poorly-drained soils due to poor soil trafficability allied to increased weight of the bandspreaders".
C	Carbon
Carbon-footprint	The amount of greenhouse gas emissions (CO_2, N_2O, CH_4) associated with the production of a specific type of agricultural produce, expressed as kg CO_2eq per kg produce (e.g. per kg beef, milk).
Carbon Navigator	Software advisory tool, developed by Teagasc, that identifies farm-specific management interventions that will reduce the carbon-footprint of the produce of that farm.
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent
COFORD	Programme of Competitive Forest Research for Development
CSO	Central Statistics Office
DO	Domestic Offsetting
EBI	Economic Breeding Index
EFs	Emission Factors quantify the greenhouse gas emissions associated with activity data (see above), and that are expressed as "emissions per activity unit", e.g.: nitrous oxide emissions per kg fertiliser N applied. Generally, the values of emission factors do not change over time, unless more accurate/representative values are obtained by new research.
EPA	Environmental Protection Agency (Ireland)

EU	European Union
FAO	Food and Agriculture Organisation
FAPRI	Food and Agricultural Policy Research Institute
FW 2025	FoodWise 2025 (in scenario analyses)
GHG	Greenhouse Gas
GJ	Gigajoule (10^9 Joules)
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
kt	kilotonne
LCA	Life Cycle Assessment
LU	Livestock Unit
LULUCF	Land-Use, Land-Use Change and Forestry
MACC	Marginal Abatement Cost Curve (see Textbox 1.1 – Section 1.1.3 for details)
Mt	Megatonne
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous Oxide
NFS	National Farm Survey
Non-ETS Sectors	Sectors of the economy that fall outside the Emissions Trading Scheme
NZ MoE	New Zealand Ministry of Environment
SEAI	Sustainable Energy Authority of Ireland
SOC	Soil Organic Carbon
Baseline Scenario	In order to assess potential environmental impacts arising from increased output and production associated with current growth due to quota abolition and FW2025, the FAPRI model was used to project activity data to 2030 and this data was used to calculated GHG emissions using IPCC methodology.
t	tonne (1000 kg)
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

In 2012 Teagasc published a Marginal Abatement Cost Curve (MACC) for greenhouse gas (GHG) emissions from Irish Agriculture (Schulte et al., 2012) and gave a commitment to revisiting the MACC at a future point in time. That initial MACC had 2020 as the horizon point. It explored the extent to which Irish agriculture could contribute to the EU 2020 Climate and Energy Package national GHG target. This target was a 20% reduction in GHG emissions relative to 1990.

In 2012 Teagasc emphasised that science, technology and policy would all continue to evolve, meaning that a new MACC would be required at a future point. Building on the work done in 2012, this new MACC now seeks to provide a more up to date picture of the achievable GHG mitigation, this time taking 2030 as a horizon point. In particular advances in **beef genetics, fertiliser formulation and manure management** mean that there are a range of new measures for inclusion. While the previous MACC focused on mitigation, this new MACC also includes carbon sequestration. A suite of land management measures, such as **pasture and cropland soil management**, **forestry sinks** and **management of organic soils** are included.

1.1. The Policy Context

Foodwise 2025: The Food Harvest 2020 development plan has been further extended under the Food Wise 2025 (FW2025) Strategy, which envisages a further increase in dairy production as well as significant expansion of the arable, pig, poultry and forestry sectors. The principal targets include

a) increasing the value of agri-food exports by 85% to €19 billion,
b) increasing value added in the agri-food, fisheries and wood products sector by 70% to in excess of €13 billion,
c) increasing the value of primary production by 65% to almost €10 billion and
d) creating an additional 23,000 direct jobs in the agri-food sector all along the supply chain from primary production to added value product development.

However, any future expansion of output will have to be carried out whilst maintaining environmental sustainability. Indeed, the strategy has adopted as a guiding principle that "… environmental protection and economic competitiveness will be considered as equal and complementary, one will not be achieved at the expense of the other." Sustainability is understood to encompass economic, social and environmental attributes and the subsequent strategic environmental assessment of FW 2025 proposed the need to embed sustainable growth into the strategy. The definition of this sustainable growth recognises the need to achieve a balance between economic, environmental and social objectives and sustainable growth should seek to increase the value added by the sector per unit of emissions (GHG or ammonia) produced.

EU Climate and Energy Legislation 2013-2020: Current and future EU Climate targets pose considerable challenges for Irish agriculture. Under the current EU 2020 Climate and Energy Package and associated Effort Sharing Decision (Decision No. 406/2009/EU), Ireland was given a 20% reduction target for the period 2013-2020. Along with Denmark, Ireland was presented with the largest reduction target as part of this agreement, with GDP per capita as the principal mechanism for the effort sharing allocated across the Member States. Importantly, offsetting emissions via carbon (C) sequestration was not allowed, due to the perceived uncertainty surrounding terrestrial C sinks.

EU Climate and Energy Legislation 2021-2030: The overall EU effort in the period to 2030 is framed by the EU's commitments under the Paris Agreement. The Paris agreement aims to tackle 95% of global emissions through 188 Nationally Determined Contributions (NDCs) which will increase in ambition over time. The agreement means that the EU has a target of a 40% in greenhouse gas emissions by 2030 compared to 1990 levels.

Ireland's contribution to the Paris Agreement will be via the NDC proposed by the EU on behalf of its Member States. A proposal on the non-ETS targets for individual Member States, the Effort Sharing Regulation (ESR), was published by the European Commission in July 2016. The ESR proposal suggests a 39% GHG reduction target for Ireland for the period 2021 to 2030 relative to 2005, based on GDP per capita. This emissions target has been adjusted downward for cost-effectiveness by 9 %, so the national target is 30% by 2030, to be achieved by linear reduction from 2021-2030 based relative to a 2005 baseline (see Figure 1.1).

In addition, Ireland has been offered flexible mechanisms, with 4% of the target achievable through the use of banking/borrowing of EU ETS allowances and 5.6% achieved via offsetting emissions by sequestering carbon dioxide (CO_2) in woody perennial biomass and soils through land use management (of forestry, grasslands, wetlands and croplands) and land-use change (from cropland to forestry for instance). The level of flexibilities are higher than those for other EU Member States, as it was recognised that Ireland had two specific difficulties in reaching targets by emissions reduction alone: 1) the ratio of Ireland's non-ETS:ETS emissions is higher than in most member states and 2) the high proportion of agricultural emissions in total Irish GHG emissions. The flexibilities allowed under the current 2020 targets (borrowing and sale/purchase of credits) are maintained for the 2020 - 2030 period.

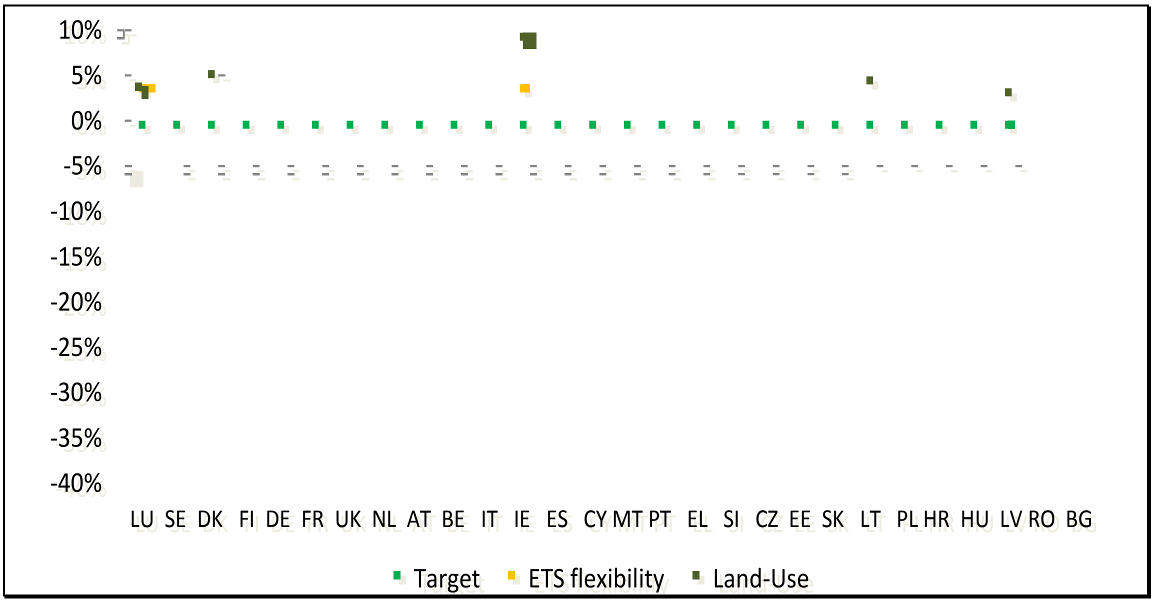
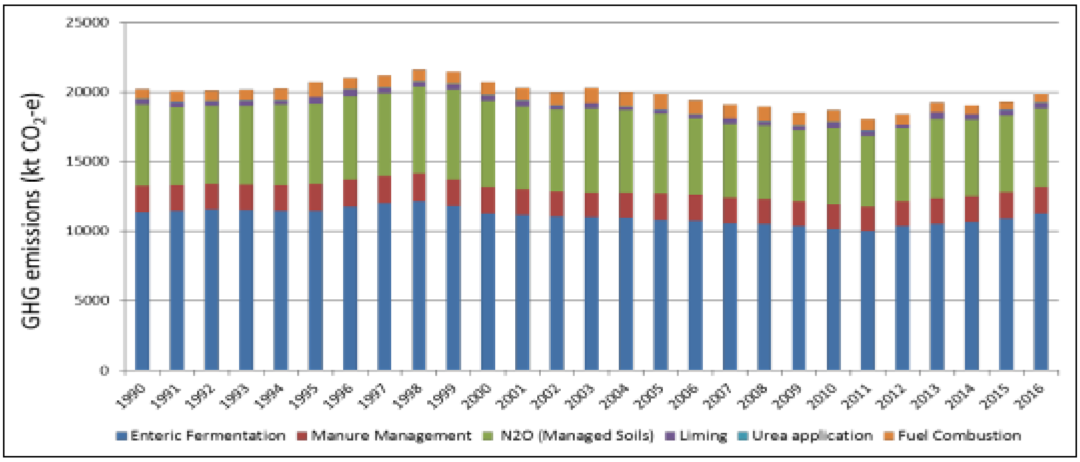


Figure 1.1: National targets for EU member states with flexibilities under the 2030 Effort Sharing Proposals (Source: 20/07/2016 - MEMO-16-2499).

Ireland's approach to the 2030 target: Individual economic sectors within Ireland do not have specific GHG emission reduction targets at this time (June 2018). However, there are challenges for the agricultural sector due to the fact that agriculture accounts for 32% of national emissions. Moreover, agriculture represents 44% of Ireland's non-ETS emissions (Duffy et al., 2015). This means that agriculture has to be part of the national solution in terms of absolute reductions in greenhouse gases. Agriculture and transport combined accounted for 73.3% of non-ETS emissions.

1.1.1. Ireland's Greenhouse Gas Emissions Profile

As illustrated in Figure 1.2, for Ireland the agriculture category (which for definitional reasons includes emissions from on farm fuel combustion and fishing) emitted 19.25 Mt CO_2-e in 2016. This represents a 1.26% reduction relative to 1990 and a 7.25% reduction relative to the period of maximum emissions in 1998 (Duffy et al., 2017). However, emissions were 2.65% above 2005 (baseline year for 2030) levels.



Source: EPA National Inventory Report 2018

Figure 1.2: Greenhouse gas emissions profile for agriculture (1990-2016)

Agricultural emissions increased by 2.7% or 0.32 Mt of CO_2-e in 2016 relative to 2015, due to higher dairy cow numbers (+6.2%) and a related increase in progeny from the dairy cow herd. Indeed there has been a 31% increase in milk production from 2012-16, with an 8% increase in emissions (Duffy et al., 2017). This reflects national plans to expand milk production under Food Wise 2025 and the removal of the milk quota in 2015. There were also increased CO_2 emissions from liming (+2.7%) and urea application (+12.8%). Other cattle, sheep and pig numbers all decreased by 0.1%, 3.3% and 1.6% respectively. Total fossil fuel consumption in agriculture/forestry/fishing activities decreased by 4.7% in 2016.

Agricultural emissions are dominated by methane (CH_4), which comprises 64% of agricultural emissions, 80% of which is attributable to bovine and ovine enteric fermentation with the remainder attributable to manure management in liquid manure systems. Nitrous oxide (N_2O) from fertiliser, manure and animal excreta deposited directly onto pasture constitutes the vast bulk of the remaining emissions (30.7%), with minor CO_2 emission sources associated with liming and urea application to land and fuel combustion.

1.2. Mitigation: The adoption of technologies

For much of the last decade, the Teagasc Greenhouse Gas Working Group has been working hard to develop technologies that would address future agricultural GHG emissions. For the purposes of development of a MACC, three key questions emerge:

a) Which technologies should farmers use?
b) Which farmers are likely to adopt each technology?
c) When will farmers adopt the technology and at what rate will the technology spread until it becomes mainstream?

1.2.1. Available Technologies

One way to mitigate GHG emissions is to produce food more efficiently i.e. with fewer inputs. For a given volume of agricultural output, this then reduces emissions to the atmosphere. Established technologies that promote efficiencies include:

- higher animal productivity (e.g. higher yields, higher fertility, higher grass growth),
- changes to production techniques (e.g. extending the ruminant animals grazing season) and
- improved nutrient management (more selective application of synthetic fertilisers)

Emerging technologies that promise to reduce greenhouse gas emissions even further include:

- improved genetic merit and
- development of novel, low-emission nitrogen fertilizers.

1.2.2. Technology Adoption

Realising the GHG mitigation potential of agriculture is ultimately dependent on farm-level decisions based on how adoption will benefit the individual farmer (Chandra, et al., 2016). Mitigation options that both reduce GHG emissions and increase farm productivity, i.e. cost-effective practices, are more likely to be adopted (Smith et al., 2007; Smith et al., 2008) than practices which would negatively affect the farmer's income.

However, the potential for increased profitability alone does not imply adoption. Each farm and each farmer is unique. Policy makers must develop a better understanding of individual farmer's decisions and behaviours, in particular at a local level due to spatial heterogeneity, if policy is to be effective and encourage adoption of GHG mitigation practices (OECD 2012).

1.3. The GHG efficiency of Irish Agriculture

Recent estimates put GHG emissions from the agriculture sector at 14-18% of global GHG emissions (IPCC 2013), with 75% arising from non-Annex 1 countries, principally South and East Asia and Latin America (Smith et al., 2007). FAO projections suggest that increases in global population and wealth will increase demand for dairy and meat by more than 50% by 2050 (Bruinsma, 2009). The FAO (2006) has projected that the increase in demand for both meat and dairy products will slow after 2030. More recent assessments forecast an 80% increase in dairy demand between 2000 and 2050 (Huang, 2010). Most importantly, there are significant concerns that this increase in food production will be associated with (among other impacts on natural resources) increased global GHG emissions from agriculture and particularly from land-use change. For example, Smith et al. (2007) estimated that, by as soon as 2020, global GHG emissions from agriculture will increase 38% relative to 1990 (24% relative to 2005). In light of the sustained future demand for dairy and meat, it is essential that the GHG emissions per unit product (GHG emissions intensity) are reduced.

The Joint Research Centre of the European Commission conducted an analysis of the carbon (C) footprint of a range of agricultural products across the EU-28 Member States. It concluded that Ireland had the joint lowest C footprint for milk production and the fifth lowest for beef production in the EU, respectively (Leip et al., 2010). This supports the finding by the FAO that the C footprint of milk is lowest in 'temperate grass-based systems', such as those that are commonplace in Ireland (FAO, 2010). This efficiency was further underlined by a study on nitrogen efficiency across European agriculture, which showed that livestock production in Ireland was the most N efficient in the EU (Leip et al., 2011). An earlier assessment and comparison of water quality shows that Ireland is in fifth place in the ranking of the proportion of 'good status' water bodies across the EU (European Commission, 2010; Wall & Plunkett, 2016).

This positive environmental performance has been driven by on-going gains in resource use efficiency by Irish agriculture since 1990. Indeed, Teagasc research showed that the C footprint of Irish produce has been reduced by c. 15% since 1990 and a 1% drop in the C footprint of milk per annum to 2025 is forecast (Schulte et al., 2012). Similarly, the 'Nitrogen-footprint' of Irish produce has been reduced by c. 25%. This means that Irish farmers now apply 25% less nitrogen fertilizer per kg food produced since 1990, through more efficient production methods and use of inputs such as fertilizer. Data from the Teagasc National Farm Survey shows that these efficiency gains present a win: win scenario for environmental and economic sustainability. For example, an analysis of data from 2013 shows that the most profitable dairy farms were those with the lowest C footprint per litre (l) of milk (O' Brien et al., 2015).

Carbon Leakage: In light of sustained or increased demand, any contraction in food production in one region in order to meet national GHG reduction targets, may simply displace that production elsewhere. Agri-food in Ireland contributes €24 billion to the national economy annually and provides up to 10% of national employment. Large reductions of the national herd in order to aid meeting emission targets while substantially reducing GHG emissions, could have a disproportionate impact on the economic and social life of rural Ireland. An analysis by Lynch et al. (2016) investigated the impact of removing the Irish suckler herd and found that while it would result in a reduction in emissions of 3 Mt CO_2-e per annum, this still would not meet a 20% pro-rata sectoral target and beef production would be reduced by 14%. This is a deficit that may be filled by countries with a higher beef C footprint, resulting in higher total global agricultural emissions. This "carbon leakage", will result in a global net increase in GHG emission if the region to which production is displaced has a higher 'emissions intensity' (GHG emissions per unit product) than the region where production had contracted. This unintended consequence of national level implementation of mitigation policy could have potentially significant adverse impacts on net global GHG emissions. Indeed, a recent analysis of the impact of EU 2030 targets concluded that pro-rata reductions for EU agriculture would result in significant leakage effects (Fellmann et al., 2018). They concluded that flexible implementation of mitigation obligations was required at national and global level and there was a need for a wider consideration of technological mitigation options. The results also indicate that a globally effective reduction in agricultural emissions requires multilateral commitments for agriculture to limit emission leakage and may have to consider options that tackle the reduction in GHG emissions from the consumption side.

Reports by the FAO (2010) and Joint Research Council (Leip et al., 2010) have shown that temperate grass-based dairy systems (such as Ireland and New Zealand) have half the emissions intensity compared with tropical grassland dairy systems (Latin America and South-East Asia) or arid grassland dairy systems, with higher emissions in tropical/arid systems principally due to higher methane emissions that resulted from reduced forage quality and associated lower animal productivity. As a result, leakage of dairy production from temperate grass based systems to tropical or arid grasslands will double or treble the emissions associated with the same amount of product. Similarly for beef production, a meta-analysis by Crosson et al. (2011) has shown wide ranges of variation across production systems and countries. Irish emissions varied from 18.9 – 21.1 kg CO_2-e kg^{-1} beef and compared favourably to Brazilian emissions, which were in excess of 30 kg CO_2-e kg^{-1} beef (Cederberg et al., 2009; Ruviaro et al., 2015). This value again excluded land-use change, which would increase five to ten-fold depending on the proportion of land-use emissions allocated to beef (Cederberg et al., 2012).

1.4. The Challenge of Mitigation

Teagasc operates ambitious research and knowledge transfer programmes on greenhouse gases, with an annual expenditure of c. € 4m from a combination of external and internal funding. These programmes focus on developing cost-effective abatement strategies for Irish agriculture. In addition, a large proportion of the Teagasc programme on efficiency and productivity is directly relevant to reducing greenhouse gases (e.g. grazing research, animal breeding and genetics, animal nutrition, animal health, tillage crop production, farm system optimization). Teagasc also coordinates the Agricultural Greenhouse Gas Research Initiative for Ireland (AGRI-I, see www.agri-i.ie), bringing together most significant research institutes on GHG research in Ireland. In terms of Knowledge Transfer, Teagasc have developed the Carbon Navigator, and in conjunction with Bord Bia, it is used as part of the Beef and Dairy Quality Assurance Schemes. A methodology to carbon footprint beef and dairy farms (O'Brien et al., 2014) was also developed and furthermore, the Teagasc Carbon Navigator informed farmers how they could further reduce their on- farm GHG emissions. This programme assessed over 50,000 beef farms and will have 100% of dairy farms complete in 2018 as part of the Quality Assurance Programme certified by the Carbon Trust. The Teagasc Carbon Navigator is being used as a decision support tool to encourage dairy farmers to reduce on-farm GHG emissions. In addition to this, Teagasc has developed an online tool, Nutrient Management Planning-online (NMP-online, https://nmp.teagasc.ie/) which assists farmers to optimise nutrient inputs on a paddock by paddock basis, hence reducing overuse of fertilisers.

Internationally, Teagasc is taking a leadership role: it is a Governing Board member of the EU Joint Programme Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI: www.faccejpi.com); Indeed, Teagasc is currently leading a European Research Area (ERA) research programme (ERA-GAS), which is investing €14.1 million euro in agricultural and forestry GHG research and is also participating in a Thematic Action Programme on Soil Carbon. The organisation participates on several working groups of the Global Research Alliance (www.globalresearchalliance.org) and it is participating in the FAO's Partnership on benchmarking the environmental performance of livestock supply chain (www.fao.org/partnerships/leap/en/). Teagasc researchers are also members of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land-Use and have Lead Authorship on the chapter relating to Food Security and Climate Change and are also engaged in the UN expert panel for Mitigating Agricultural Nitrogen.

2. Marginal Abatement Cost Curves (MACC)

2.1. The 2012 MACC Analysis

The 2012 GHG MACC, the first of its kind for Irish agriculture, envisaged an increase in agricultural GHGs in the short term from 18.8 Mt CO_2-e in 2010 to 20.0 Mt CO_2-e by 2020, a relative increase of 1.2 Mt CO_2-e, or c. 7% (Donnellan & Hanrahan, 2012). Against this reference scenario, the Teagasc MACC analysed the potential of individual measures for climate change mitigation. Costs to the farmer arising from the measures were calculated in euro per ton of carbon dioxide equivalent saved.

The 2012 MACC was selective in the mitigation options it included. It encompassed only those measures that were relevant to the characteristics of Irish farming and where both data on abatement potential from completed scientific research and activity data for Ireland were available (Schulte & Donnellan, 2012). It was largely based on experimental results, but where necessary, expert judgement was also used. In total, 15 mitigation measures were included. Where measures were perceived to interact with each other, the potential of individual measures was adapted to prevent double accounting of mitigation potential.

In the 2012 MACC assessment, the total maximum biophysical abatement potential of the mitigation measures, using the IPCC (2014) methodology amounted to just under c. 2.7 Mt CO_2-e yr^{-1}. Of this total, c. 1.1 Mt CO_2-e of the accountable abatement potential was attributed to the agricultural sector, while much of the remainder was attributable to fossil fuel offsets in terms of biofuels. The abatement potential of biofuel/bioenergy measures (including anaerobic digestion of pig slurry), which are attributed to the transport and power generation sectors, accounted for 1.6 Mt CO_2-e yr^{-1}.

Almost all of the 1.1 Mt CO_2-e yr^{-1} abatement potential that could be attributed to the agricultural sector consisted of measures relating to improved production efficiency ("green" measures"). These included dairy economic breeding index (EBI), extended grazing, improved live-weight gain in beef cattle, improved N-efficiency and minimum tillage. Fossil fuel displacement from bioenergy was envisaged to come from biomass and bioenergy crops and woodchip from forestry as well as anaerobic digestion (AD) from pig slurry. It is clear that while heat generation from woodchip is growing, the anticipated adoption of biomass crops has not occurred and the establishment of a significant AD industry in Ireland is still in a developmental phase.

As carbon sequestration was not allowable under the 2020 Climate and Energy Package, sequestration measures were not considered in the 2012 MACC assessment.

Textbox 2.1: What is a Marginal Abatement Cost Curve?

A Marginal Abatement Cost Curve (MACC) is a graph that visualises the abatement potential of GHG mitigation measures, and the relative costs associated with each of these measures. Figure 1.1 below provides a simplified, hypothetical example of a MACC.

A MACC provides two elements of information:

1. It ranks the mitigation measures from cost-beneficial measures (i.e., measures that not only reduce GHG emissions, but also save money in the long-term) to cost-prohibitive measures (i.e., measures that save GHG emissions, but are expensive in the long-term). Cost-beneficial measures have a "negative cost", and are those in Figure 1.1 below the x-axis, on the left-hand side of the graph. Cost-prohibitive measures are above the x-axis, on the right-hand side of the graph.

2. It visualises the magnitude of the abatement potential of each measure, as indicated by the width of the bar.

In addition, a MACC commonly includes an indication of the price of carbon credits on the international market. "Cost-neutral measures" are those measures that carry zero cost in the long term. Measures that cost money (above the x-axis), but cost less than the price of carbon are called "cost-effective measures", as their implementation is cheaper than the purchase of carbon credits.

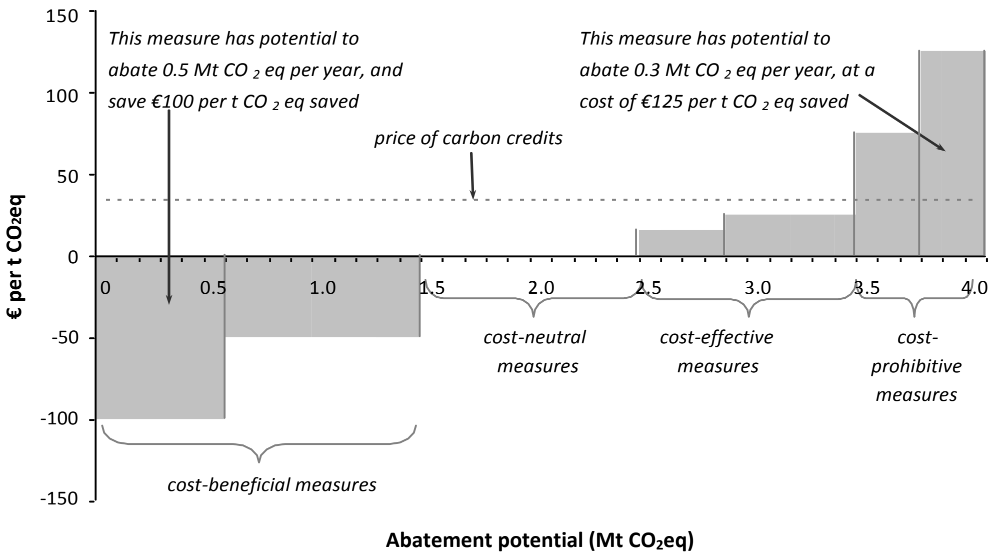


Figure 2.1: Hypothetical example and explanation of a Marginal Abatement Cost Curve (MACC)

In the hypothetical example above, cost-beneficial, cost-neutral and cost-effective measures account for an abatement potential of 1.5, 1.0 and 1.0 Mt CO_2eq, respectively, giving a total abatement potential of 3.5 Mt CO_2eq. The remaining 0.6 Mt CO_2eq of abatement potential is associated with cost in excess of the price of carbon credits, and hence deemed cost-prohibitive.

2.2. Objectives and Approach in the Current Study

The objective of the current analysis was to assess the abatement potential and associated costs/benefits of GHG mitigation measures associated with agriculture, and to present these as a MACC. The ultimate aim of this exercise is to provide objective information and a platform for discussion for the consultation process on the development of a national climate policy.

Approach: The impact of a range of mitigation measures (see below) were assessed for their potential to reduce agricultural GHG emissions, by incorporating them into a 'top-down' flow inventory approach based on the IPCC Good Practice Guidelines (IPCC, 2014) and using identical approaches to those used for the calculation of the Environmental Protection Agency (EPA) national inventories for agriculture and land-use. Activity data was sourced from multiple sources, including the Central Statistics Office (CSO), Department of Agriculture, Food and the Marine (DAFM) and EPA. The advantage of this approach was that the additive impacts of measures on national GHG emissions could be assessed collectively. This meant that interactions between measures on GHG emissions could be accounted for in this type of MACC. Cross compliance with other environmental impacts, such as the National Emissions Ceilings (NEC) Directive and Nitrates Directive were also considered. So, for example, the impact of land drainage on N_2O emissions was assessed, but the impact on improved number of grazing days on methane could also be quantified.

Conversely, the impact of increasing the proportion of protected urea fertiliser used relative to calcium ammonium nitrate (CAN) is to decrease GHG emissions through reduced N_2O emissions, but it also increases GHG emissions through additional CO_2 emissions from fertilisers. Cross-compliance issues were also addressed. Reduced crude protein in pig diets, for instance, not only reduces GHG emissions through reduced N_2O emissions, but improves air quality by also reducing ammonia (NH_3) emissions. For all measures, total emissions for a category were generated by multiplying an activity (e.g. Dairy cow numbers) times an emission factor (kg CH_4 per head). Where possible, Tier 2 emission factors were used. Indeed, the adoption of disaggregated Tier 2 N_2O emission factors represented one of the major modifications in this MACC assessment relative to the previous iteration in 2012. The main disadvantage of this national level approach is that inherent farm to farm variation is not captured, with the national level approach reliant on average farm circumstances.

Cost Assessment: The net costs of the measures were based on the estimated technical costs and benefits of the mitigation measures at the farm level, on a partial budget basis. This approach took into account the costs and benefits (both annual changes and capital investments) arising from the positive and negative change in expenses and income associated with the changes in farming activities and outputs. The costs and benefits are provided at 2015 values.

The costs presented are the marginal costs per annum for the quantity of CO_2-e abated (i.e. the additional costs a farmer will bear for introducing a technique and the associated emissions reduction achieved). These are net costs, reflecting the additional costs that are incurred in addition to the current cost for an activity (e.g. buying fertiliser, economic breeding index, etc.) minus the benefits of the mitigation measures at the farm level. Costs were estimated as the 'unit cost' of techniques, defined as the annual additional costs that a farmer incurred as a result of adoption of an abatement measure. This includes the annualised cost of additional capital, repairs, fuel and labour costs and fertiliser N savings. Costs and income accrued were annualised over the commitment period (2021-2030) with a discount rate of 4% per annum in order to generate Net Present Value (NPV) with

$$NPV = \sum_{t=0}^{n} \frac{Cost_t - Benefit_t}{(1+r)^t}$$

Where $Cost_t$ = cost of measure in year t, $Benefit_t$ = Benefit in year t, r = the discount rate, t = the time (duration of the measure).

This approach is particularly important for measures such as AD where, due to the nature of the investment, the net profitability will be achieved beyond the 2030 commitment period.

Uncertainty & Sensitivity Analysis: Sensitivity of the abatement potential was assessed on individual measures (in terms of uptake rate, price of inputs and cost savings, % reductions, and area applicable, etc.) and on factors impacting on the whole sector (future activity data such as animal numbers, fertiliser use, etc.). To this end, a number of scenarios comprising different growth trajectories for dairy and livestock production have been generated (Donnellan et al., 2018).

2.3. Future Scenario and Initial Selection of Measures for the MACC

2.3.1. Sectoral Scenarios

GHG emission reductions will need to be achieved relative to the level of GHG emissions in 2005, since this is the year against which reduction targets are based. However, the level of agricultural activity in the coming years will not be the same as in 2005. It is therefore necessary to project the future level of activity and the associated impact on greenhouse gas emissions.

The FAPRI-Ireland model (Donnellan & Hanrahan, 2006; Binfield et al., 2009) has been used extensively in the analysis of agricultural and trade policy changes in Ireland for close to 20 years. Using the FAPRI-Ireland model, Donnellan & Hanrahan (2011) had previously assessed the impact of Food Harvest 2020 on animal numbers and fertiliser use in order to estimate future agricultural GHG emissions in conjunction with the EPA.

In the current analysis, the FAPRI-Ireland model was used to provide a baseline projection of the future level of activity in Irish agriculture. Reflecting the fact that the future is uncertain, the model was also used to derive five further scenarios in addition to the baseline scenario reflecting differing levels of overall agricultural activity. Given that the bovine sector is the principal source of Irish agricultural GHG emissions, the scenarios mainly differ in terms of the size of the total cattle population, the composition of the total cattle population and the associated volume of synthetic fertiliser that is used.

For the baseline scenario (hereafter denoted as S1) and the five other scenarios (S2 through to S6), the model was then also used to project the total level of agricultural GHG emissions. Importantly, these projections of GHG emissions coming from the FAPRI-Ireland model do not consider the effect of mitigation actions and in that sense, for each of the scenarios analysed, the projected level of GHG emissions can be considered a worst case outcome. Detailed descriptions of the scenarios can be found in an accompanying document (Donnellan & Hanrahan, 2018). The related impact of this activity data on ammonia emissions is elucidated in an accompanying ammonia MACC analysis (Lanigan et al., unpublished).

Baseline Scenario (S1)

The projected level of activity under the Baseline for the principal sectors of Irish agriculture is now described.

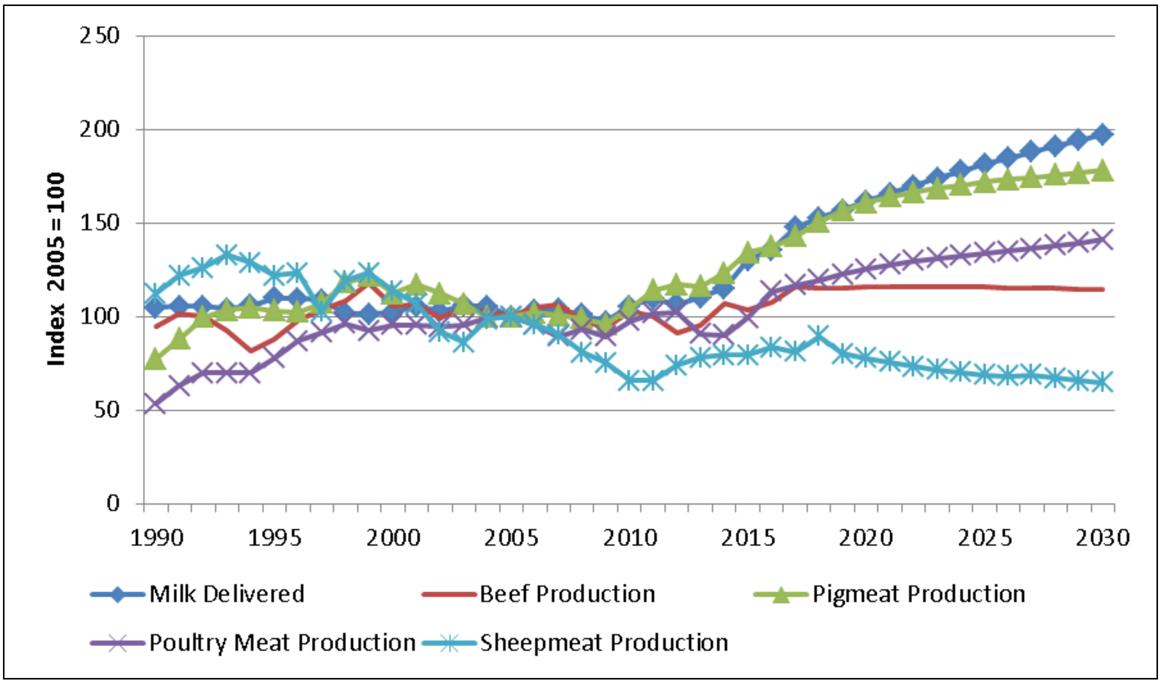
Baseline Bovines

***Change to 2030 relative to 2005**:* The total cattle population is projected to be 6% higher in 2030 than it was in 2005. There is also a significant change in the composition of the bovine population, with an increase in dairy cow numbers by 2030 of 60% relative to 2005. The population of other cattle decreases by 4% by 2030 relative to 2005. The volume of milk produced increases by 97% relative to 2005 and the volume of beef produced increases by 14% (Table 2.1, Figure 2.1).

***Change to 2030 relative to 2016**:* Relative to 2016 the total cattle population is projected to be 2% higher in 2030. There is a still a significant change in the composition of the bovine population, with an increase in dairy cow numbers by 2030 of 22% relative to 2016 (Table 2.1). The population of other cattle decreases by 2% by 2030 relative to 2016. The volume of milk produced increases by 46% relative to 2016 and the volume of beef produced increases by 6% (Figure 2.1).

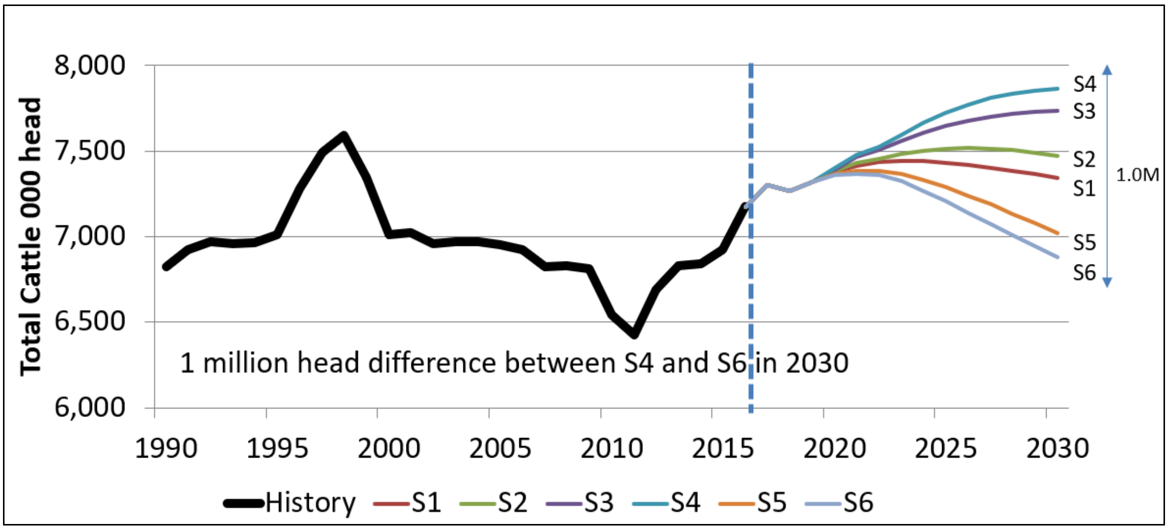
Table 2.1: Six Scenarios for the size of the projected Total Cattle Population in 2030.

	2005	2016	2030	2030 vs 2005	2030 vs 2016
		Million Head		% change	% change
Historical	6.951	7.173			
S1			7.342	6%	2%
S2			7.475	8%	4%
S3			7.738	11%	8%
S4			7.865	13%	10%
S5			7.018	1%	-2%
S6			6.880	-1%	-4%



Source: FAPRI-Ireland Model

Figure 2.1: Index (Base 2005) of historical and projected production volumes S1 Scenario.



Source: FAPRI-Ireland Model

Figure 2.2: Total Cattle Population: Summary of Scenarios S1 to S6.

Baseline Sheep

Change to 2030 relative to 2005: Relative to 2005 total sheep numbers are projected to decline by 45%, it is important to emphasise that much of this projected decrease has already occurred over the last decade. Sheep meat production in 2030 is projected to decline by 35% relative to 2005. As with the decline in sheep numbers, most of the projected reduction in sheep meat production has already occurred historically.

Change to 2030 relative to 2016: Relative to 2016 total sheep numbers are projected to decline by 25% by 2030. Sheep meat production in 2030 is projected to decline by 23% relative to 2016.

Baseline Pigs

Change to 2030 relative to 2005: The sow herd is projected to be smaller in 2030 relative to 2005, but the major driver of pig numbers historically has been increasing sow productivity (piglets produced per sow) which is also a factor in the projection period. There has also been an upward trend over time in pig slaughter weights. Relative to 2005 there is projected to be a 17% increase in total pig numbers by 2030. This is associated with a 78% increase in pig meat production over the period 2005 to 2030.

Change to 2030 relative to 2016: Relative to 2016, the sow herd is projected to grow slightly by 2030, but the major driver of the projected increase in pig numbers continues to be sow productivity (piglets produced per sow) which continues to increase. There is also growth in pig slaughter weights. Relative to 2016 there is projected to be a 26% increase in total pig numbers by 2030. This is associated with a 29% increase in pig meat production over the period 2016 to 2030.

Baseline Poultry

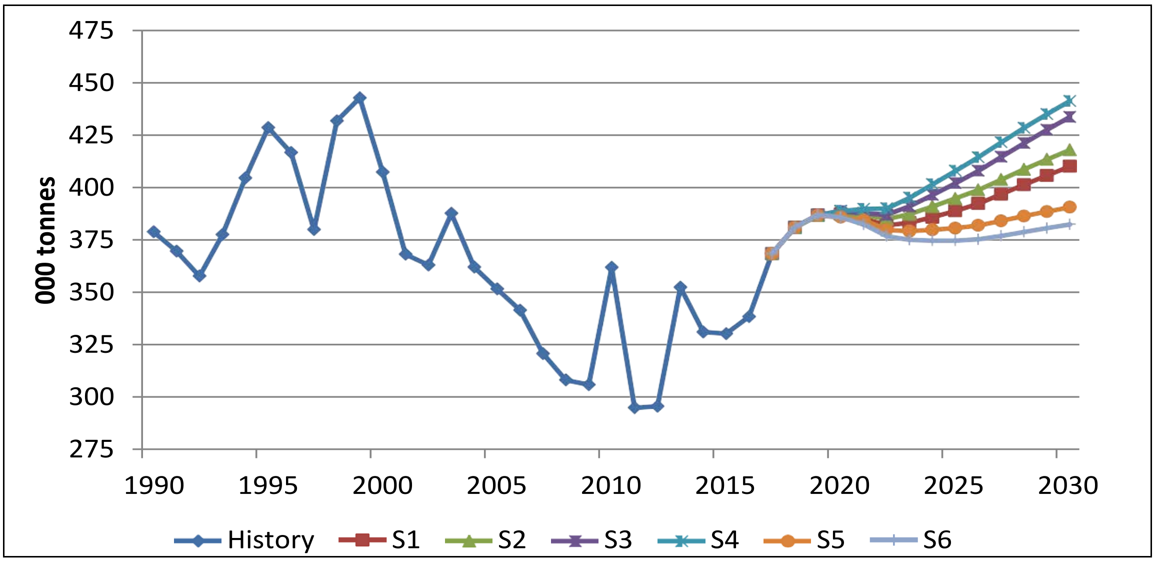
Change to 2030 relative to 2005: Relative to 2005, there is projected to be a 41% increase in the volume of Irish poultry meat production by 2030.

Change to 2030 relative to 2016: Relative to 2016, there is projected to be a 24% increase in the volume of Irish poultry production by 2030. The strong growth in Irish production is largely in line with projected growth in the domestic use of poultry meat in Ireland.

Baseline Fertiliser

Change to 2030 relative to 2005: Over much of the period 2005 to 2016 synthetic fertiliser use has changed by relatively small magnitudes. However, usage is projected to increase in the coming years, due largely to the projected increase in milk production. Relative to 2005, a 17% increase in nitrogen use is projected by 2030.

Change to 2030 relative to 2016: While fertiliser use is projected to increase over the period 2016 to 2030, the growth in the level of total fertiliser applied under the Baseline (S1) scenario is not dramatic considering the change in total levels of agricultural activity. While the more fertiliser intensive dairy sector increases its production, the area allocated to dairy also increases, limiting the increase in overall stocking rate. In addition, the price of feed relative to fertiliser declines, making purchased feed marginally more attractive economically than grass as an energy source and limiting the increase in the intensity of fertiliser use on a per hectare (ha^{-1}) basis over the projection period. Relative to 2016, a 21% increase in nitrogen use is projected by 2030.



Source: FAPRI-Ireland Model

Figure 2.3: Projected implication of the six scenarios for the level of synthetic nitrogen use.

Summary of Scenarios S2 to S6

Scenarios S2 to S6 look at differing developments in the bovine herd (dairy cow herd, suckler cow herd and associated progeny) which give rise to differing outcomes in terms of the total cattle population (and its composition) and the associated level of milk and beef production. These projections are summarised below, with further details available in Donnellan et al. (2018).

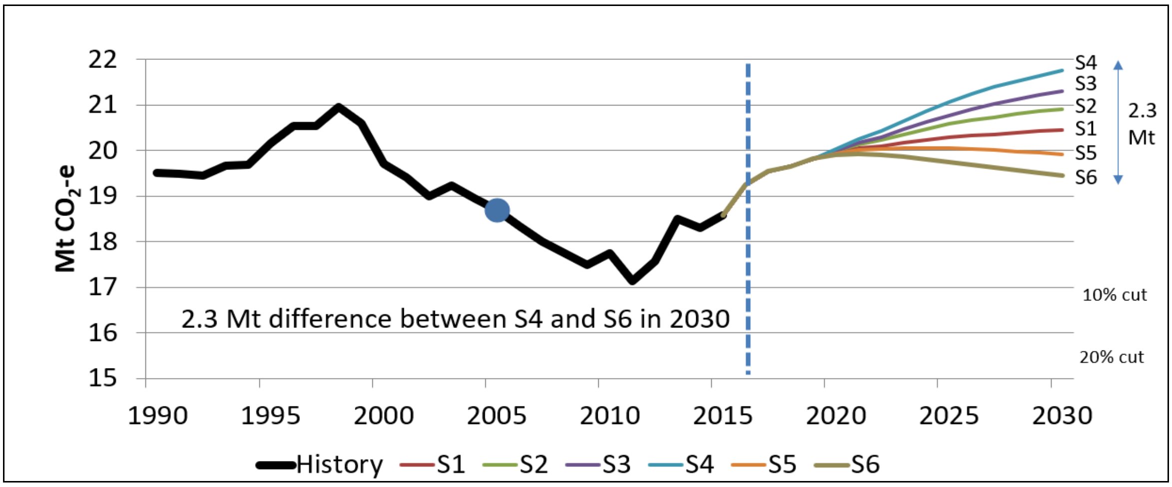
Summary of scenario activity levels and associated GHG emissions

Among the six scenarios examined, the highest cattle population is observed under the S4 scenario, which is the scenario with the largest increase in the dairy cow population and the smallest reduction in the suckler cow population.

Scenario S6 has the lowest cattle population, given that it has a lower rate of growth in the dairy cow population and a larger reduction in the suckler cow population. For comparison, the Baseline (S1) scenario takes an intermediate path between the S4 and S6 scenarios. By 2030 there is a difference of 1 million head of cattle between the upper band (S4) and lower band (S6) of the scenarios examined. The projected levels of the total cattle population under the six scenarios are reproduced in Figure 2.2.

The FAPRI-Ireland model also provides projections of the impact on synthetic nitrogen use arising from the differing cattle populations under each of the six alternative scenarios analysed and the declining agricultural land base used in the alternative scenarios examined. The projections of total synthetic nitrogen use in Irish agriculture over the period to 2030 under each of the six alternative scenarios are presented in Figure 2.3.

Taking the overall levels of activity for all of the agricultural sectors (including nitrogen use), across all of the scenarios analysed, allows for the projection of GHG emissions under the Baseline (S1) and across the 5 other scenarios (S2-S6). The highest level of GHG emissions is associated with the S4 scenario and the lowest level of emissions is associated with scenario S6 (Figure 2.4). In 2030 the span across the 6 scenarios amounts to 2.3 Mt CO_2 eq.



Source: FAPRI-Ireland Model

Figure 2.4: GHG emission projections under the six scenarios – this analysis excludes mitigation actions

The projected level of GHG emissions in 2030 are presented in Figure 2.4 and Table 2.2, along with the deviation in 2030 emissions relative to the 2005 reference level for emission reductions. Note that projected emissions levels do not consider mitigation measures and should be considered worst case in terms of emission levels.

Table 2.2: Historical and Projected Agricultural GHG Emission (excludes mitigation).

	2005	2016	2030	2030 vs 2005	2030 vs 2016
		Mt CO_2-e		% change	% change
Historical	18.69	19.24			
S1			20.45	9%	6%
S2			20.91	12%	9%
S3			21.31	14%	11%
S4			21.75	16%	13%
S5			19.92	7%	4%
S6			19.45	4%	1%

2.3.2. Measures included in MACC

Numerous agricultural mitigation measures for GHG abatement have been reported in the international literature (see e.g. Moran et al., 2010, Eory et al., 2016). However, both the relative and absolute abatement potential of each of these measures, as well as their associated costs/benefits, are highly dependent on the bio-physical and socio-economic environments that are specific to individual countries. In other words- it is not possible to simply duplicate the choice of abatement measures assessed, their associated abatement potential, or the resultant costs/benefits from studies which assess the agriculture sector in other countries. Therefore, for the MACC curve presented in this report, individual measures were selected and included on the basis of the following criteria: (1) Measures must be applicable to farming systems common in Ireland and (2) Scientific data, from completed peer- reviewed research, must be available on the relative abatement potential of each measure, as well as the relative cost/benefit. For each measure, activity data (actual and projections) must be available to assess the total national abatement potential and associated cost/benefit.

On this basis, the **agricultural mitigation measures** included were:

1) Improved beef liveweight gain,
2) Improved beef maternal traits,
3) Improved dairy economic breeding index,
4) Extended grazing,
5) Nitrogen (N) use efficiency,
6) Improved animal health,
7) Increased use of sexed semen,
8) Inclusion of clover in pasture swards,
9) Switching N fertiliser formulation from CAN to protected urea,
10) Reduced crude protein in pig diets,
11) Draining wet mineral soils,
12) Slurry chemical amendments,
13) Adding lipids/fatty acids to dairy diets,
14) Low-emission slurry spreading.

Land-use mitigation strategies to enhance carbon (C) sinks or reduce C loss from agricultural soils included were:

15) Improved grassland management,
16) Water table manipulation of peaty agricultural grassland soils,
17) Forestry,
18) Inclusion of cover crops in tillage,
19) Inclusion of straw incorporation in tillage.

Energy mitigation measures included were:

20) Increased farm energy efficiency,
21) Increased use of wood biomass for energy generation,
22) Increased use of short rotation coppice and miscanthus biomass for heat production,
23) Increased use of short rotation coppice for electricity production,
24) Biogas production by anaerobic digestion of slurry and grass,
25) Biomethane from biogas
26) Oilseed rape for biodiesel
27) Sugar beet for bioethanol

A detailed description of each individual measure is given in Appendix 2.

3. Summary MACC Results and Recommendations

3.1. Total Mitigation Potentials

Achieving both 2020 and 2030 interim climate targets as well as delivering carbon neutrality will be extremely challenging for the agriculture, forestry and land-use (AFOLU) sectors. Mitigation of methane and N_2O (1.85 MtCO_2-e), combined with carbon sequestration (2.97 MtCO_2-e), and energy displacement (1.37 Mt CO_2-e) delivers a 6.19 Mt CO_2-e per annum saving for the periods 2021-2030 at a net cost (including efficiency savings) of circa €34 million per annum. When cost savings from efficiency measures are removed, the gross cost of measures is €223 million per annum. The associated measures are presented in Figure 3.1 to Figure 3.3. Details in respect of these measures are provided in Appendix 2.

Mitigation of greenhouse gases was broken down into three parts: a) Agricultural mitigation of CH_4 and N_2O, b) Land-use mitigation and c) energy mitigation. New measures, not previously included in the 2012 MACC assessment, include altered fertiliser formulation, drainage of mineral soils, beef genomics, dietary strategies (reduced crude protein in pigs and increased fatty acids in bovine diets) and the use of sexed semen and slurry amendments during storage.

3.2. Agricultural Mitigation

The average annual mitigation potential for methane and nitrous oxide was calculated assuming linear uptake of measures to be **1.85 Mt CO_2-e yr^{-1}** and this represents the mean mitigation potential between 2021-2030. (Figure 3.1). However, by 2030, when maximum uptake is envisaged to have occurred, the mitigation potential will be 3.07 Mt CO_2-e yr^{-1}. *This highlights the urgent requirement for a strong link between research and knowledge transfer to encourage earlier practice change and the prompt development of policy measures and incentives to encourage uptake of mitigation options.* While many efficiency measures (particularly those predicated on genetic improvement) are incremental in nature, the uptake of *technical* measures and nitrogen-use efficiency could be accelerated via a combination of advisory/education and policy measures. If full uptake of these measures occurred at the beginning of the commitment period, they would account for 2.05 Mt CO_2-e per annum of agricultural mitigation at a net cost of €56.7 million.

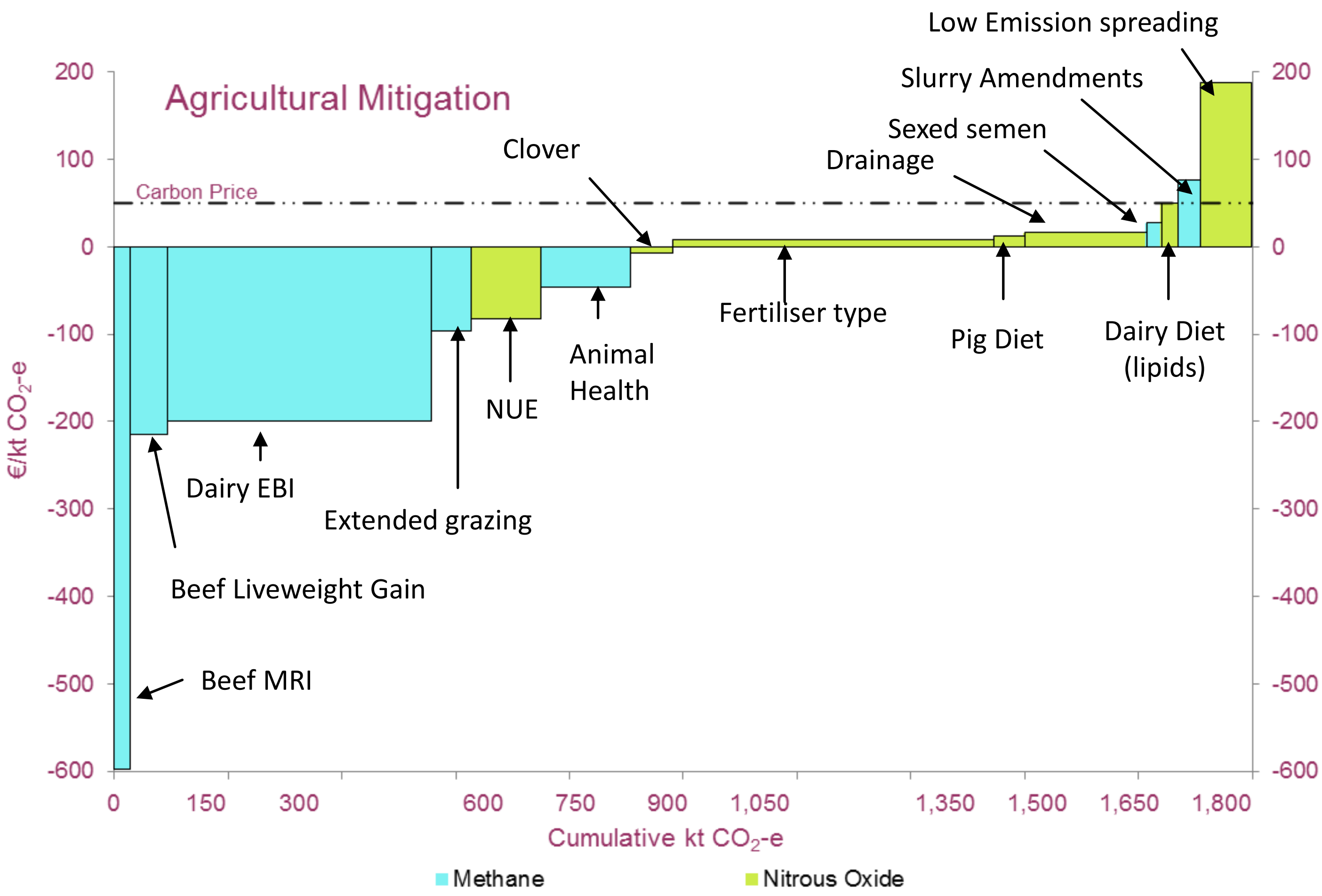


Figure 3.1: Marginal Abatement Cost Curve for agriculture for 2021-2030 (methane and nitrous oxide abatement). Values are based on linear uptake of measures between the years 2021-2030 and represent the mean yearly abatement over this period. Dashed line indicates Carbon cost of €50 per tonne CO_2.

3.2.1. Efficiency Measures

Cost-negative strategies mainly comprised of efficiency measures which concurs with the previous 2012 analysis. These measures indirectly reduce methane by reducing the number of animals required to produce a given amount of meat or milk. The increase in efficacy of these measures is incremental over time. Measures consist of dairy EBI, improved beef efficiency via optimised liveweight gain and improved maternal traits, extended grazing from draining heavy mineral soils, and improved animal health (dairy, beef and sheep). The total cost-negative methane abatement was 0.75 Mt CO_2-e yr^{-1}, which is **additional** to 1.1 Mt CO_2-e yr^{-1} from the 2012 MACC. In addition, improved nitrogen-use efficiency, via optimizing soil pH and extension of clover in pasture swards, delivered an extra 181 kt CO_2-e yr^{-1} and would result in an 8% reduction in fertiliser use between 2021 and 2030. The cumulative saving associated with all efficiency measures could deliver €136 million per annum. However, it should be noted that these figures **do not** include significant national expenditure that has been made. In particular, under the beef genomic scheme, the exchequer has spent approximately €300 million in terms of improving the national beef herd. This expenditure relates to the measures 'Improved liveweight gain' and 'Improved beef maternal traits'.

An increase in production efficiency is a win-win situation that leads to lower emissions per unit product and lower costs to the producer. Where either production volume or animal numbers *are held constant*, these measures also result in the production of a lower *absolute* amount of emissions. However, the supply response of farmers to increased profitability also needs to be considered and this may lead to increased overall production, offsetting some of the improvement in emissions intensity. In this case, any reductions attributable to improved emissions intensity of produce would be partly or fully negated due to increases in total animal numbers and could even result in an increase of national GHGs. Additionally, savings from improved nutrient-use efficiency would have to be accompanied with actual reductions in nutrient inputs in order to realise absolute emission reductions. These rebound and backfire effects from increased efficiency have been documented for various sectors (Barker et al., 2009; Frondel et al., 2013). Indeed, this has occurred in the dairy sector, where a 38% increase in milk production between 2012 and 2016 has occurred, but only an 8% in methane emissions.

3.2.2. Technical Measures

These measures mainly impact on emission factors and thus reduce the emissions associated with a given activity, rather than the total amount of that activity. These measures include fertiliser formulation, crude protein and fats in diets, slurry amendments and land spreading management of animal manures. While most of these measures incur a cost, they result in an absolute emission reduction and are quantifiable under IPCC national reporting structures (IPCC, 2014b). These measures are estimated to deliver 1.08 Mt CO_2-e yr^{-1} mitigation between the period 2021-2030. Slurry amendments, fertiliser formulations, reduced crude protein, and low emission slurry spreading also had co-benefits in reducing ammonia emissions. The total net cost of these measures is €39.3 million per annum.

3.2.3. Upstream Emissions

This study quantified the impact of mitigation on GHG emissions from Ireland. As such, it complied with IPCC rules and accounted for emissions arising within national boundaries. However, upstream emissions in terms of feed and fertiliser manufacture and downstream emissions (transport, refrigeration) in intensive livestock production (dairy, beef, pig meat) can account for 32%-24% of total livestock emissions, with approximately 40% arising from energy emissions and 60% from land-use emissions (Weiss & Leip, 2012). As such, there is extra potential mitigation associated with the manufacture of concentrate feed and fertiliser. Among the measures investigated in this and the previous MACC were improved N efficiency, clover, slurry management, and cover crops. These would be examples where, under IPCC rules which define emission categories, the effects from lower fertilizer use can be attributed to agriculture, but the effects due to lower production is attributed elsewhere. Furthermore, as all mineral fertilizer in Ireland is imported, an emissions reduction due to lower fertilizer production (due to lower fertiliser use in Ireland) would not be reflected in any part of the Irish GHG inventories. If however, the reduction from fertiliser production were included, GHG emissions are reduced by a further 0.42 Mt CO_2-e yr^{-1}.

Similarly, under IPCC rules, the GHG and land-use impacts associated with soya production are not included in the GHG emission of Irish agriculture, although emissions from soya meal production are circa. 800 kg CO_2-e per tonne meal (Sonesson et al., 2009). The extensive grass-based nature of Irish bovine production means that concentrate usage in bovine diets is low (7-20%) in Irish systems compared to confinement bovine systems prevalent in continental Europe. Efficiency measures such as dairy EBI and reduced beef finishing times limit the further need for concentrates, as more milk and beef are produced per kg intake, while extension of the grazing season also reduces the proportion of concentrates in the animal diet.

3.3. Land-use and Land Management to Enhance Carbon Sequestration

The Commission Effort Sharing proposal (20/07/2016 - MEMO-16-2499) included the allocation of 26.8 MtCO_2-e of land-use, land-use change and forestry (LULUCF) credits to Ireland over the 10-year period (5.6% of 2005 base year emissions). The Commission confirmed that Member States with a larger share of emissions from agriculture were allocated a higher share of LULUCF credits within this proposal. This equates to 2.68 Mt CO_2-e yr^{-1}. It is projected that the full allocation could be met and indeed, exceeded by at least 0.29 Mt CO_2-e yr^{-1} (2.97 Mt CO_2-e yr^{-1}) with the bulk of the sequestration due to forestry (Figure 3.2). However, a substantial portion could also be delivered by optimal management of grasslands, water table manipulation of organic soils and tillage management (cover crops and straw incorporation). Indeed, this analysis has been conservative in terms of both replanting rates for forestry and re-wetting of organic soils. If afforestation doubled to 10,000 ha per annum and rewetting of organic soils in agriculture doubled in area, an extra 1.4 Mt CO_2e of sequestration could be achieved annually. In addition, restoration of blanket bogs used for industrial peat extraction could also contribute to reducing CO_2 loss from the land-use sector. However, two caveats associated with these measures should be noted.

a) The full allocation of LULUCF sequestration might not be allocated with Agriculture. In order to reach future post-2030 targets, greater flexibilities will be required in terms of utilising C sinks in order to approach Carbon Neutrality. The total costs of mitigation for AFOLU emissions are calculated to range from €78 – 118 M per annum.
b) At present, under the Kyoto Protocol Ireland has only elected forestry and re-wetting of organic soils as measures under Articles 3.3/3.4. The Land Management Factor (i.e. C sequestration) associated with grassland and tillage management has currently not been elected, although there is a large body of research currently being undertaken and it is envisaged that these factors should be included by the 2021-2030 commitment period.

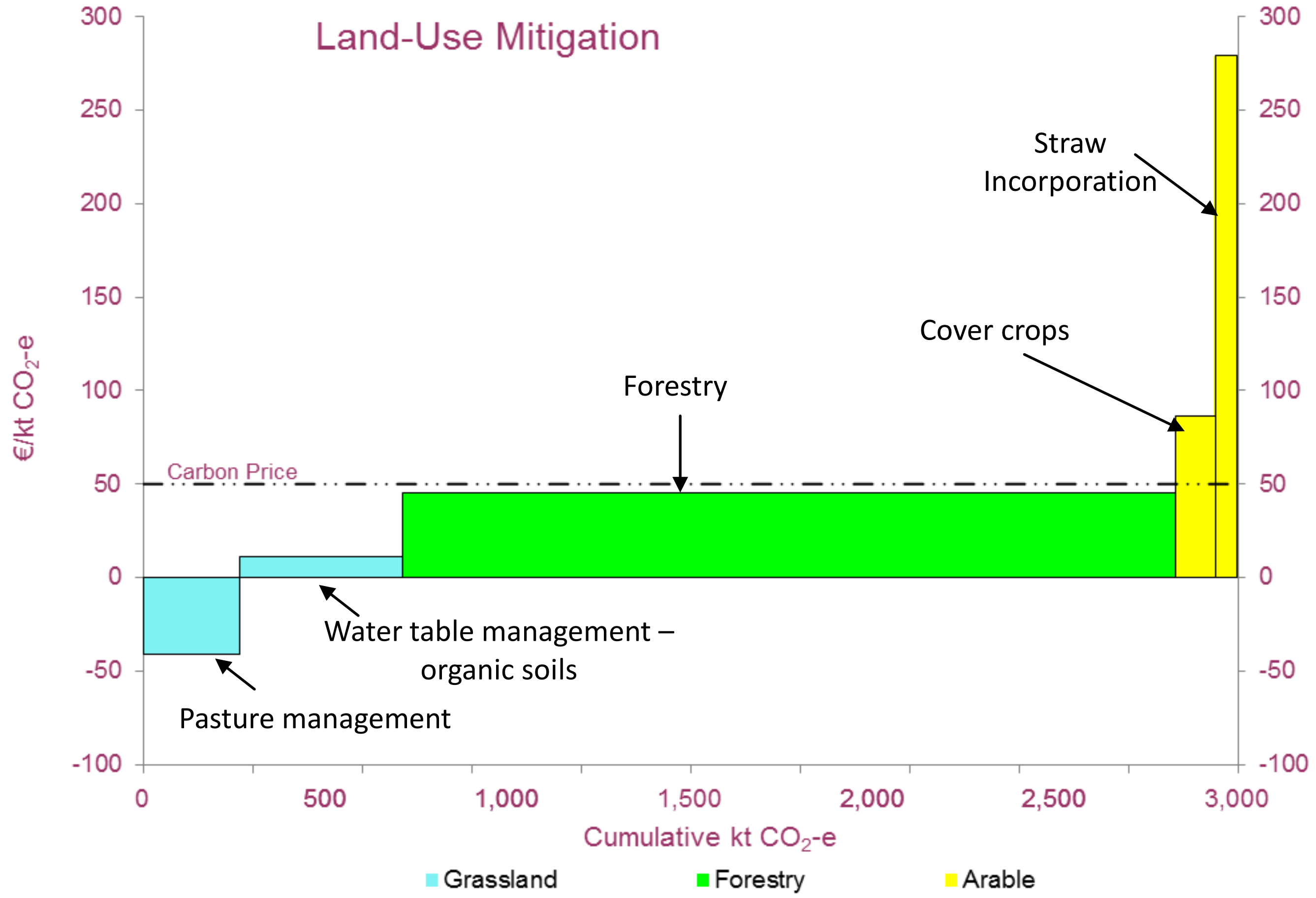


Figure 3.2: Marginal Abatement Cost Curve for agriculture for 2021-2030 (carbon sequestration associated with land management and land-use change). Values are based on linear uptake of measures between 2021-2030. Dashed line indicates Carbon cost of €50 per tonne CO_2.

3.4. Energy: Offsetting fossil fuel emissions

The capacity for offsetting fossil fuel emissions is highly uncertain. In the previous iteration of the MACC, bioenergy was estimated to deliver 1.4-1.6 Mt CO_2-e yr^{-1}, yet much of this has remained unrealised as the land area of biomass crops is low and anaerobic digestion uptake is very low. **A mean annual mitigation potential of 1.47 Mt CO_2-e yr^{-1} between the years 2021-2030** could be realised (see Figure 3.3) and is primarily met by forestry utilisation in heat and power generation but would also require a significant adoption of grass-based anaerobic digestion. In addition, 25,000 ha biomass crops, mainly short rotation coppice (SRC), would be needed for both electricity and heat generation. A further 0.3 Mt CO_2-e yr^{-1} could be met by biofuel production (biodiesel from OSR and bioethanol from sugar beet). However, the EU sustainability criteria for biofuel production demands a 75% total savings in fossil fuel GHG across the full life-cycle of biofuel crop production (RED II, 2018). For this to occur, any new bioethanol or biodiesel plants being established would also have to bio- refine other products that would also displace fossil fuel-generated products (e.g. plastics) for this target to be achieved. Total cumulative costs associated with bioenergy measures are estimated at €58 million per annum.

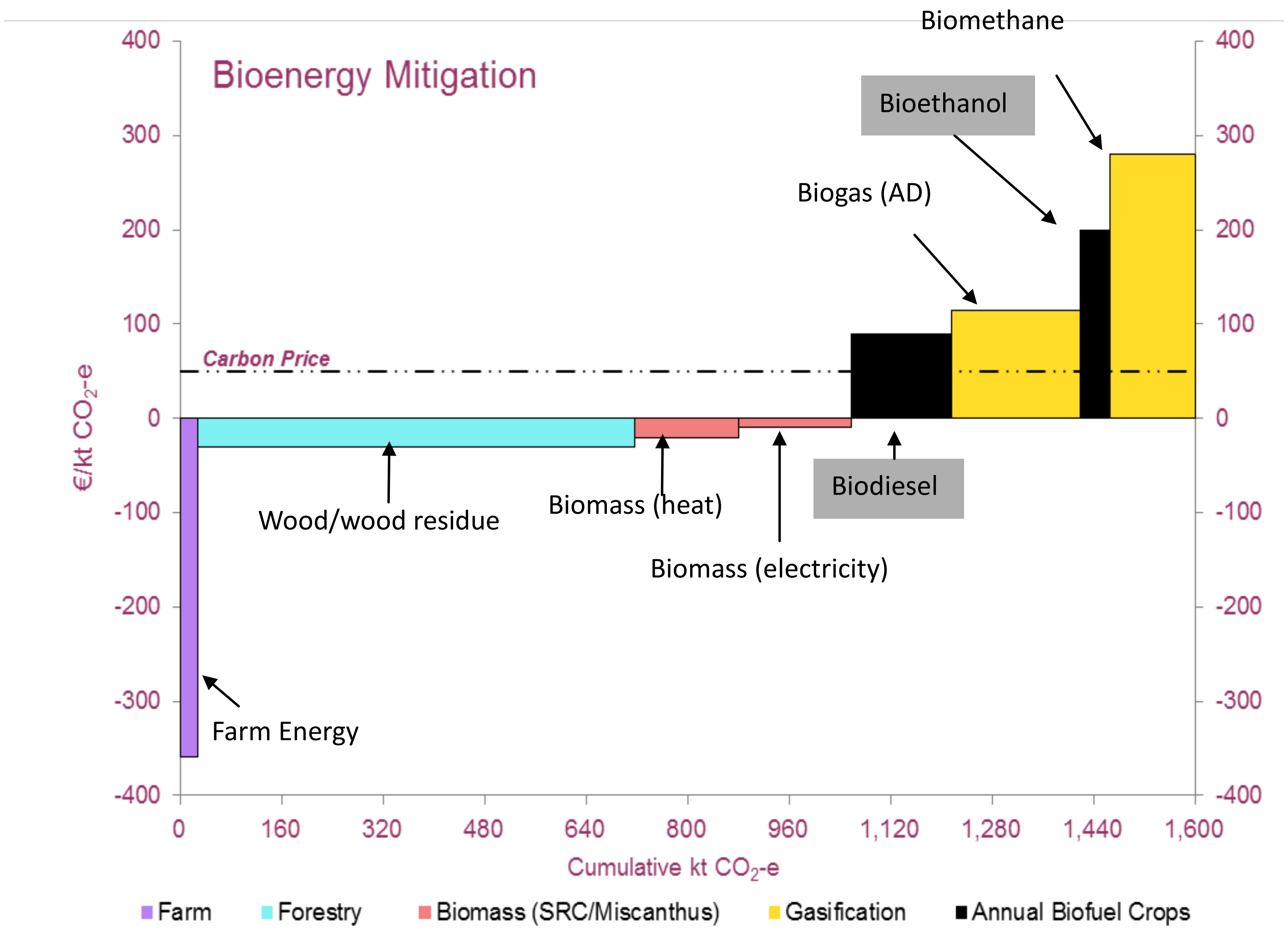


Figure 3.3: Marginal Abatement Cost Curve for agriculture for 2021-2030 for bioenergy produced in the agriculture and forestry sectors. Values are based on linear uptake of measures between 2021-2030 and represent the mean yearly abatement over this period (Abbreviations: AD = Anaerobic digestion, SRC = Short Rotation Coppice, OSR = spring/winter oilseed rape). Dashed line indicates Carbon cost of €50 per tonne CO_2. *Note: Bioethanol/biodiesel does not meet RED II sustainability criteria at present.*

3.5. Implications for 2030 Targets

For sensitivity purposes, total cost-effective measures were defined at three different carbon prices: those measures costed at or below €25, €50 and €150 per tonne CO_2-e abated (Figure 3.4). Currently the UK has a price floor of £18 per tonne CO_2-e, while France and Germany are considering setting floors of between €28-€100 per tonne CO_2-e. In this MACC analysis for Ireland, most of the agricultural abatement (1.52 Mt CO_2-e or 82%) and energy mitigation (1.1 Mt CO_2-e or 75%) was achievable at a C price of no more than €25 per tonne CO_2-e, but only 24% of identified total land-use mitigation was achievable at that price. However, at the higher €50 per tonne CO_2-e price point, most of the land-use mitigation was encompassed, with 5.7 Mt CO_2-e or 89% of total mitigation falling within this price threshold. Most of the remaining 11% of mitigation was priced at between €100-150 per tonne CO_2-e.

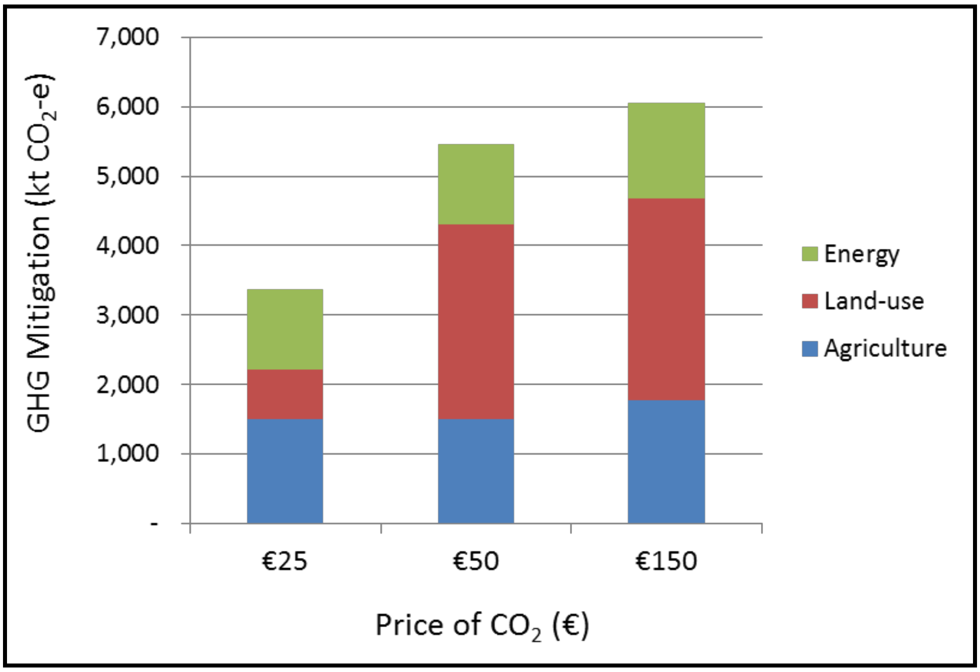


Figure 3.4: Total mitigation potential per annum for agriculture (blue), land-use (red) and energy (green) sectors at a carbon price of €25, €50 and €150 per tonne CO_2-e.

The impact of agricultural mitigation is shown in Figure 3.5. Assuming linear uptake over the period 2021 to 2030 for all measures, total GHG emissions, with agricultural measures included, will decrease by an average of 9.2% relative to the baseline over the 2021-2030 period (Figure 3.5). This also represents a 1.5% reduction in emissions over the whole commitment relative to 2005. If it is assumed that, as part of the non-ETS, agriculture has to deliver a *pro-rata* 20% reduction in sectoral emissions (with LULUCF and energy mitigation *separately* contributing to national/non-ETS), then there remains a 3.46 $MtCO_2$-e per annum distance to target in 2030 (Figure 3.5).

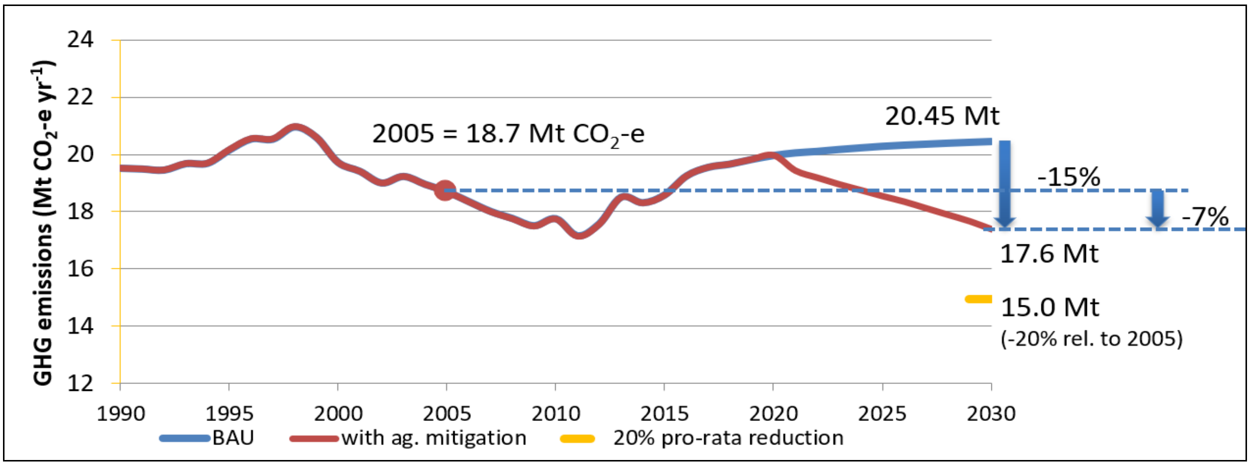


Figure 3.5: Agricultural GHG emissions from 1990 and projected to 2030, without (blue) and with (red) mitigation. The orange line represents a *pro-rata* 20% reduction in sectoral emissions.

Mitigation from land-use/land-use change and forestry (LULUCF) and energy will deliver further reductions to non-ETS and/or total national emissions across the commitment period. The mean reduction from LULUCF is capped at 26.8 Mt CO_2-e for 2021- 2030 or a mean annualised reduction of 2.68 Mt CO_2-e as detailed earlier and along with agricultural mitigation can deliver a 9.6% reduction on 2005 emissions. Further mitigation from energy/bioenergy will deliver 1.37 Mt CO_2-e to either non-ETS or ETS, depending on where the energy displacement occurs (e.g. electricity generation or residential heating).

Table 3.1. Agricultural GHG emissions from 1990 and projected to 2030, and the cost effective abatement potential at a C price of €50/tonne.

	Actual emissions (Mt CO_2-e yr^{-1})			Projected emissions or abatement under S1	
	1990	2005	2016	Mean over 2012-2030 period	2030
Total Agricultural emissions (ex. Fuel)	19.51	18.69	19.24	20.28	20.45
Agricultural mitigation				1.73	2.89
Land-Use mitigation				2.80	3.50
Energy mitigation				0.99	1.31
Total mitigation				**5.52**	**7.70**

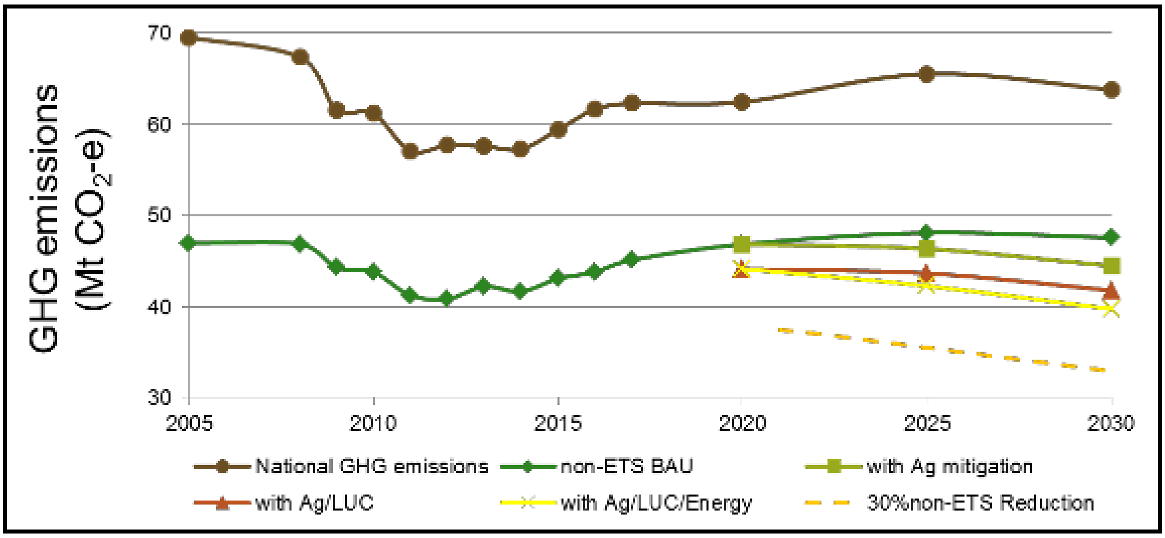


Figure 3.6: National GHG emissions 2005-2030 (orange), non-ETS emissions 2005-2030 under business as usual scenario (blue), with agricultural mitigation (red), with addition land-use mitigation (green) and energy mitigation (yellow). The gold dashed line represents a 30% reduction in non-ETS emissions relative to 2005.

Achievement of *further* abatement from the sector could be achieved via greater sequestration in forests (through higher planting rates) and mitigating CO_2 emissions from organic soils, but this would require Ireland being granted a greater flexibility in terms of utilisation of C sinks than is currently envisaged. Other options to increase mitigation would include management of the overall level of activity in the agricultural sector. Given that most of Ireland's agricultural GHG emissions derive from the cattle population, the size of the total cattle population would then become an area of focus. The extent of the associated economic cost would depend on which parts of the bovine sector were affected. Additionally, there would be a cost beyond agriculture, extending to the processing industry and related sectors via the multiplier impact. There would also be societal costs that are less easily quantified. Ultimately there would also be carbon leakage effects as reduced Irish production and reduced emissions would be offset by higher production and higher emissions elsewhere internationally.

A recent study by the EU Joint Research Centre on the impact of 2030 GHG reduction targets on agriculture at an EU level found that implementation of a pro-rata reduction across the component parts of the non-ETS sector resulted in a) adverse impacts on agricultural production in most Member States and the EU a whole and b) a net increase in global agricultural emissions as production moves to less emissions efficient countries (Fellmann et al., 2017). Recommendations included that specific mitigation targets for EU agricultural emissions might require a more flexible implementation, also taking into account where emissions are least costly to reduce. In addition, it was concluded that it might be necessary to take net imported emissions into account when setting national mitigation targets.

3.6. Trade-Offs and Synergies with Ammonia Emissions and Nitrates Directive

Aside from the pressures to reduce GHG emissions, the requirement to also reduce ammonia emissions is urgent not only in the context of the National Clean Air Strategy As a principal loss pathway for agricultural nitrogen, ammonia emission reductions should be a key focus for improving farm efficiency and sustainability. This is particularly relevant in the context of the Food Wise 2025 Strategy. Similar to GHGs, by 2030 ammonia is projected to increase by 6% relative to 2005, with a 1% reduction target from 2020 to 2030 and a 5% reduction target set for 2030 onwards. An ammonia MACC analysis (Lanigan et al., 2015) has previously been published and is currently being updated. It is relevant to this analysis as ammonia indirectly contributes to N_2O production and because individual ammonia mitigation and GHG mitigation measures can be either complementary or antagonistic.

The analysis revealed that there is a maximum potential ammonia mitigation of 22.3 kt NH_3 yr^{-1} by 2030 at a cost of €79M per annum, with most abatement achieved via the use of a urea fertiliser that is coated with a urease inhibitor, the adoption of trailing shoe/trailing hose technologies for slurry spreading and slurry amendments. These measures have the potential to reduce GHG emissions by 168.6 kt CO_2-e yr^{-1} mainly from measures 11 (crude protein in pigs), 12 (slurry amendments) and 14 (low-emission slurry spreading). A residual 4.9 ktCO_2-e yr^{-1} of mitigation arises from other manure management measures such as drying poultry litter and covering external slurry stores that would have previously been uncovered. It should be noted that these measures are priced at above €100 tCO_2-e^{-1} yr^{-1} abated, but that they should still be considered to be cost effective due to the consequence that much of the abatement is related to avoiding indirect N_2O, while their cost in terms of abatement per tonne of NH_3 are relatively low (circa €4 per kg NH_3).

Some of these measures are covered under the National Mitigation Plan under measure AF2E. Most of the measures analysed have either a positive or at worst marginally negative impact on water quality, particularly dietary strategies, N efficiency and enhanced pasture management that reduce N excretion and fertiliser formulation. Two GHG mitigation measures which are antagonistic in term of their impact on ammonia emissions are extended grazing and drainage of mineral soils. Extended grazing, while reducing GHG emissions would lead to more N excretion on pasture (as opposed to housing) and could increase nitrate leaching, but if associated with increased N use efficiency, the risks will be low. Drainage of mineral soils will reduce N_2O emissions but could increase N leaching. Increased N use efficiency could enhance biodiversity where multi-species swards are used in the suite of measures to increase efficiency. Other measures, such as increased broadleaf forestry should also significantly enhance biodiversity, while low-emission slurry spreading will help preserve heathland and bog habitats. The spreading of AD digestate, which is high in available N could also be antagonistic to ammonia and nitrate emissions.

3.7. Relationship between Mitigation Options and Draft National Mitigation Plan

Clearly a number of the measures listed here are associated with measures listed in the National Mitigation Plan. Knowledge Transfer (KT) and associated measures are covered under measures AF2B, AF4, AF5, AF7, AF8 and AF9 in the National Mitigation Plan (see Department for Communications, Climate Action & Environment 2016 for code references). Knowledge transfer has been identified as being vital in maximising the emissions reduction capacity, due to the impact which the uptake rate of emissions reduction measures has on the total emissions reductions achieved across the whole period, with reductions estimated at between 4.7 and 6.1 Mt CO_2-e yr^{-1} for AFOLU measures. Beef genomics (Measure AF2A) is estimated to deliver circa. 110 kt CO_2-e yr^{-1} from 2021 to 2030. Measure AF2E – Targeted Agricultural Modernisation Schemes (TAMS II) includes altered slurry spreading and manure management from housing and accounts for 102 kt CO_2-e yr^{-1} from 2021 to 2030, but has a proportionately larger impact on reducing ammonia emissions (see Section 3.3.5). The Pasture Profit index (Measure AF5) contributes to grassland sequestration and bioenergy (Measures RE2, RE4) as grass would be the principal feedstock to agricultural-based AD (see Section 4) which is estimated to deliver 0.71 Mt CO_2-e yr^{-1}, while AF6 Animal By-Products can contribute 0.14 Mt CO_2-e yr^{-1}, a proportion of the total AD mitigation. Forestry is covered under AF10 and will deliver over 2.1 Mt CO_2-e yr^{-1} reduction.

3.8. 2050 Towards Carbon Neutrality: The Role of Land-use and Functional Soil use

Using 2050 as a time horizon, the 2050 Carbon Neutrality report (Schulte et al. 2013) investigated scenarios whereby sectoral C neutrality could be achieved. It included strategies and technologies that may not yet be readily implemented in the short term, but that may become available or feasible in the period up to 2050. Defined by the difference between gross agricultural emissions and agricultural offsetting, the emissions gap was projected to likely equate to circa 13 Mt CO_2-e or two-thirds of total agricultural emissions and this could widen in the event of reductions in forestry sequestration. Under the pathways analysed, increased sequestration from forests and grasslands and increased fossil fuel displacement were seen as likely pathways. However, these scenarios would require significant land-use change and potentially the adoption of a national land-use strategy. Under these scenarios, substantial increases in afforestation (up to 20,000 ha per annum) and management of organic soils is required. Any land–use strategy should include a framework for managing soils to enhance C sequestration and reduce soil C losses. Highly productive, trafficable soils should be prioritised to remain in agricultural production, enhanced grassland sequestration via optimal management should be promoted, soil organic carbon (SOC) on organic soils should be maintained and, where appropriate, C emissions in cases where organic soils have been drained should be reduced (Schulte et al. 2016, O'Sullivan et al. 2016). **Also, in order to maximise the use of sinks in offsetting emissions, a cap on the use of C sequestration would have to be**

removed from future post 2030 EU legislation, as there is capacity beyond the current limit to sequester or reduce losses of CO_2. Several initiatives funded by both the EPA and DAFM have begun which will develop analyses and decision-support tools to assess the impact of policy on functional land use. Irish grasslands are already high in SOC, with high levels of recalcitrant (permanent) C stocks and the development of policies/measures to incentivise stock maintenance are urgently required (Torres-Sallan et al., 2017).

Ultimately, achieving timely and substantial levels of mitigation will require a multi-actor approach involving primary producers, the food industry, research/KT and policymakers working in concert. Effective large-scale mitigation will involve a closer linkage between research/analysis to the development of relevant policies and effective translation on the ground via KT. Thus, a coherent linkage of research and analysis, KT and policy-making will be required in order to maximise adoption.

4. Knowledge Transfer

As both the 2020 and 2030 GHG reduction targets are multi-annual targets (effectively targets for cumulative emissions reduction over time), the total amount of abatement achieved will be highly dependent on rates of uptake. Ultimately, the quicker adoption of measures should lead to a larger cumulative emission reduction. This means that understanding barriers to uptake and the role of KT in overcoming obstacles for adoption will both be more important than ever.

Teagasc has a number of research programmes designed to develop a more detailed understanding of the individual farmer decision making process. This has included the development of a typology of farmers based on their attitudes, where such attitudes are an important factor in the decision to adopt GHG mitigation practices. Other research is informing the direction of support services, not only towards those more likely to adopt new GHG mitigation practices, but also understanding where current agri-KT actions are less effective.

However, research in itself will not lead to emission reductions without strong linkage to KT. There are twin roles of research and KT: whereas research into new GHG mitigation options aims to further reduce the carbon-intensity of farms that are already carbon-efficient, KT efforts focus on narrowing the spread in carbon-intensities between the most efficient producers and the main body of producers (see Figure 4.1). This highlights the urgent requirement for a stronger link between research and knowledge transfer to encourage practice change and the adoption of mitigation measures by Irish farmers. For example, Irish dairy farmers with agricultural education or who participate in farmer discussion groups are more likely to adopt the mitigation practice of extended grazing (O'Shea et al., 2015).

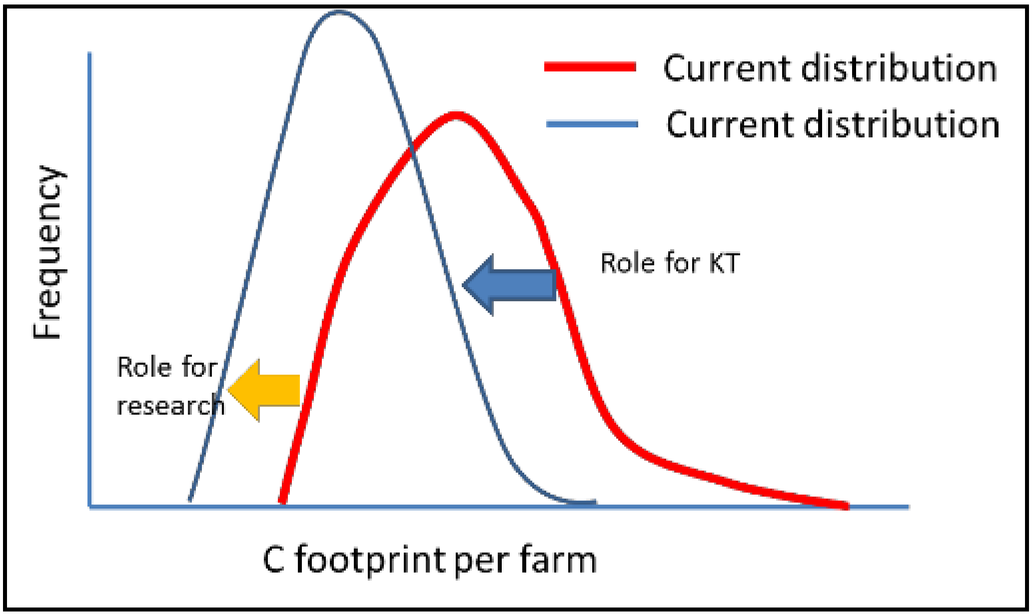


Figure 4.1: Conceptual illustration of the roles of research and KT in reducing the carbon intensity of produce: while new research outcomes can further reduce the minimum carbon footprint of produce, the role of KT programmes is to narrow the frequency distribution and lower the average GHG intensity, by bringing the carbon intensity of the majority of producer closer to that of the top 10% most efficient producers.

Therefore, emissions reductions can only be realised if the desired mitigation actions are supported by a comprehensive KT programme. This finding concurs with one of the main recommendations of the Environmental Analysis of the FoodWise 2025 Strategy (Farrelly et al., 2015), commissioned by DAFM. In response to this KT challenge, Teagasc have a number of initiatives to aid in the uptake of new abatement measures. In the National Mitigation Plan, three have been highlighted (AF4 & AF7 BETTER Farms, AF5 Pasture Profit Index, PastureBase Ireland and AF9 Carbon Navigator). Each of these measures as stand alone would do little to reduce GHG emissions. However, taken as part of a linked strategy between research, KT and policy, they are key tools for achieving climate targets. Key measures include:

- Teagasc and Bord Bia have jointly developed the Farm Carbon Navigator, an on-farm KT tool to aid farmers and advisors in selecting cost-effective / cost-beneficial mitigation options that are customised for their individual farming system and environment. Importantly it is a simple tool, free of jargon, to help farmers decide what will work on their farm. These cost-effective mitigation measures were identified in the 2012 MACC (Schulte et al., 2012) and will be updated following publication of the 2018 MACC with the inclusion of new measures. Current measures include EBI, grazing season length, increased calving rate, better slurry management and improved nitrogen use efficiency. All beef farms and dairy farms in the Bord Bia Quality Assurance scheme have been carbon- audited and have also received a Carbon Navigator report. The Navigator report compares a farm's performance relative to similar farms and highlights the economic and GHG impact of adoption of the above measures. If all these measures were adopted by dairy and beef farmers in the scheme, a maximum 1 Mt CO_2-e yr^{-1} would be abated by 2020 and a further 0.9 Mt CO_2-e yr^{-1} by 2030.

- Improved economic breeding index, improved animal health and improved pasture management will reduce emissions. Maximum adoption of EBI and animal health would reduce GHG by 0.38 Mt CO_2-e yr^{-1} between 2017-2030.
- PastureBase Ireland (Hanrahan et al., 2017) was developed in order to help farmers maximise utilisation of pasture by paddock grazing, along with optimising levels of Lime and NPK to maximise output per livestock unit. Taken in isolation, maximising grass growth might lead to an increase in GHG due to increased use of fertilisers. However, combined with nutrient management planning (see below) and optimised slurry management, optimal pasture utilisation could reduce N_2O and also enhance carbon sequestration as long as overstocking does not occur. Grassland sequestration via enhanced growth and slurry management is estimated at a maximum of 0.3 Mt CO_2-e yr^{-1}. In addition, in agriculture-based AD facilities, the principal feedstock will most likely be grass rather than slurry. In addition, PastureBase Ireland aims to help farmers make better decisions around grassland management, thus ensuring that the grass offered to the animals is of the highest quality resulting in reduced methane emissions (Wims et al., 2010). This will reduce methane emissions, by minimising the amount of silage and supplemental feed in the diet and improving feed quality and promoting grass regrowth.
- Nutrient Management Planning (NMP online): Nutrient Management Planning is required in order to fulfil the terms of the Nitrates Directive. Teagasc has developed an online system for developing nutrient management plans for environment and regulatory purposes called **NMP online**. This tool allows farmers to optimise nutrient requirements on a paddock by paddock basis. It requires farmers to soil test their fields and the tool then provides maps of the N, P, K and lime requirements in order to optimise output. The data underlying the tool has been obtained from Teagasc research and is synthesised in the Major and Micro-Nutrient Advice for Productive Agricultural Crops 'Green Book' (Wall & Plunkett, 2016). Optimal liming reduces the requirement for mineral fertiliser and higher pasture primary production will increase soil C sequestration, which will in turn increase nutrient availability. NMP online, used in conjunction with pasture growth monitoring will thus optimise Net Primary Productivity and hence sequestration. Optimal nutrient management will also decrease ammonia emissions as optimising N fertiliser replacement value by definition requires lower ammonia loss and reduces nitrate leaching and runoff. Optimal pasture management and increased N use efficiency will deliver 0.4 Mt CO_2-e yr^{-1}.
- The BETTER beef farms programme, has at its heart, increases in efficiencies. Now in Phase 3, previous phases have led to increased gross margins by 52% for farmers

who joined the programme in 2012, with technical efficiencies delivering 83% of this improvement. Other farmers in every region of the country have had the opportunity to see these improvements implemented on these farms. Key strategies for Phase 3 include increased fertility of the beef herd, improved animal health, increased soil fertility and incorporation of clover into 20% of swards, all measures which are projected to decrease GHG emissions, improve water quality and reduce ammonia emissions. Teagasc see the BETTER farm programme as a key demonstration tool with which to improve uptake of measures.

- Monitoring the progress of adoption of abatement measures and assessing the success of tools such as C Navigator and NMP online, will also be a key requirement over the next commitment period. Teagasc's National Farm Survey (NFS) has been incorporating features into the survey that will allow for the monitoring of measures such as timing and application technique of slurry spreading, grazing season length, fertiliser type and use, EBI and herd makeup, finishing times and health. In addition, a survey of farm facilities is urgently required in order to inform measures for the abatement of GHG and ammonia emissions arising from manure management.
- The Heavy Soils Programme. The programme aims to improve the profitability of grassland farms on heavy soils through the adoption of key technologies including appropriate drainage solutions, high quality pasture management, land improvement strategies and efficient herd management. Drainage of these mineral soils can aid in the reduction of N_2O which is highest in poorly drained soils. However, the drainage of humic (gleysols and podsols) and histic (peat) soils would result in substantial CO_2 emissions to the atmosphere, that would dwarf any non-CO_2 benefit.

5. Future Measures

The 5th Assessment Report of the IPCC states that within the category AFOLU demand side measures may play a role in mitigating climate change, even though they might be difficult to implement (Smith et al. 2014). Demand-side measures are based on the assumption that a lower demand will lead to lower prices and in turn lower production and therefore lower emissions arising from the production of goods and services. This refers to demand both by producers that require raw materials and energy to produce goods and services, as well as demand by private consumers. Measures include those that result in a lower demand for fertilizer imports, lower feed concentrate imports or lower food production through reduced food waste and a change in western industrialized countries towards diets lower in meat and milk-based proteins. For example, overconsumption in Australia represents ~33% GHG emissions from food (Hadjikakou, 2016).

However, demand-side measures cannot be directly accounted for under the Kyoto Protocol rules and the European Climate Policy Framework because responsibilities for emissions from the production of goods and services are placed with producers and not with consumers. This consideration would not be a problem in the absence of international agri- food trade, but in reality, trade is significant and particularly so for Ireland. If a reduction in demand in one country results with reduced production and associated emissions in another country, the country responsible for the lower demand will not receive credits for this. Moreover, as the majority of Irish agricultural produce is exported, Ireland has little or no legislative control over the bulk of consumer demand for this produce. The latest iteration of the UK Agricultural MACC (Eory et al., 2015) also includes a qualitative assessment of mitigation effects from reducing food demand through dietary changes. They conclude that consumption changes hold a significant potential for reducing emissions, but that lower domestic demand (such as would result where Ireland unilaterally implemented measures to reduce domestic demand) would mainly be compensated by higher exports.

Other measures, including the extended use of precision farming, particularly in terms of reducing fertiliser inputs and soil specific fertiliser recommendations, may offer substantial capacity to reduce N_2O emissions, although more research is needed. In addition, a great deal of research into the rumen microbiome is currently being undertaken. A better understanding of the role and makeup of the rumen microbial community on methane emissions may allow for measures to directly influence methane emissions, either by inhibiting methane production or altering the rumen microbial community that results in lower methane emissions. Similarly, future research in terms of the soil microbiome is revealing the interactions between soil fungi and bacteria and their influence on N_2O emissions. The manipulation of these communities and the development of natural nitrification inhibition in plants or microbes may further decouple soil GHG emissions from nutrient input. The re-introduction of nitrification inhibitors onto the market, assuming inclusion of a residue standard into the Codex Alimentarius, could also further reduce N_2O emissions.

Biorefining and second-generation biofuels will also play a role in further displacing fossil fuel emissions, improving the sustainability of biofuel production and creating circular economies, as can a more widespread distribution of energy saving and energy generation (e.g. solar PV) in the landscape. The recycling of other waste streams (spent mushroom compost, etc.) into the production of biochar and other soil conditioners can also play a role in reducing environmental impacts and improving soil health and C sequestration.

6. Summary and Recommendations

Achieving both 2020 and 2030 interim climate targets as well as delivering carbon neutrality will be extremely challenging for the agriculture, forestry and land-use (AFOLU) sectors. Mitigation of CH_4 and N_2O, combined with carbon sequestration, can deliver a 4.82 Mt CO_2-e emission reduction for the periods 2021-2030, at a net cost of €20 million per annum. This cost comprises potential efficiency savings of €147 million and gross costs of €167 million. It should be noted that efficiency measures may not deliver absolute GHG emissions reductions in the context of sectoral expansion but will limit any increases. An additional reduction of 1.47 Mt CO_2-e can be contributed via fossil fuel displacement via energy saving and the use of bio-energy at a further net cost of €58 million per annum. Further reductions to 2050 will require an investment in research to develop breakthrough mitigation options combined with an integrated knowledge transfer strategy and the development of policies that will incentivise adoption or a fundamental change in Irish agriculture.

Table 6.1: Summary of the mean potential GHG mitigation for the period from 2021-2030 and the maximum mitigation in the year 2030. Cost effective mitigation is achieved at €50 t^{-1} CO_2-e

MACC Category	Mean CO_2-e saving 2021-2030 Mt yr-1	CO_2-e saving in 2030 Mt yr-1	Mean CO_2-e saving 2021-2030 @ €50 per tonne Mt yr-1	CO_2-e saving in 2030 @ €50 per tonne Mt yr-1
Agricultural Mitigation	1.85	3.07	1.73	2.89
Land Use Mitigation (Carbon sequestration land management & land-use change†)	2.97	3.89	2.80	3.50
Energy Mitigation - Fossil Fuel Displacement	1.37	2.03	0.99	1.31
Total	**6.19**	**8.99**	**5.52**	**7.70**

†The maximum allowable sequestration is 26.8 Mt CO_2-e over the commitment period or 2.68 Mt CO_2-e yr^{-1}.

Recommendations:

- Continued effort to promote maximum adoption of those efficiency measures identified in the abatement cost analysis is required, especially in terms of beef genomics and dairy EBI. Appropriate policy measures are required to incentivise best available technologies (particularly low-cost measures) that have been identified.
- Targeted KT to encourage grassland farmers to switch from calcium ammonium nitrate fertilisers to nitrogen fertilisers with proven lower emissions in Irish conditions.
- Increased N efficiency via appropriate soil nutrient management, slurry management and where possible, the use of grass legume mixtures is required as well as a move to more GHG-efficient fertilisers.
- Enhancing C sinks and reducing soil C losses are key strategies to reducing sectoral emissions. This will principally be achieved through increased afforestation, reducing losses on organic soils and enhancing pasture sequestration. Policies and mechanisms for incentivising soil C management and further incentives for afforestation are required. Removal of the cap on the use of sequestration in a post- 2030 EU agreement would also be required as there is further capacity to either sequester or reduce losses of carbon beyond the current 26.8 $MtCO_2$-e limit.
- The development of a national AD policy to encourage the adoption of grass-fed

AD to provide biomethane for the national grid and transport. The increased demand for grass may encourage increased pasture growth and utilisation on lower stocked beef farms.

- There is a need for national policy to optimise the total activity to a level that delivers on Foodwise targets, but also allows reductions in GHG to be delivered.
- Continue to develop Irish specific Tier 2 emission factors to further refine the national inventory and to assess the impact of mitigation measures on N_2O, CH_4 and CO_2 emissions. The incorporation of grassland and tillage management effects into the national inventories is required. There is also a pressing need for better activity data recording particularly in terms of farm facilities and documenting of behavioural change.

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Appendix 1. Capturing Mitigation: Inventory Improvement & Mitigation Verification

Emissions inventories are compiled for individual sectors of a nation-state by collating those activities that produce emissions (such as fertiliser spreading, CH_4 belched by dairy cows, fossil fuel burning from cars, etc.). For each activity, a quantitative stock is measured, usually from national statistics (e.g. cattle population, fertiliser sales) and multiplied by an emission factor (EF) (e.g. amount of CH_4 produced from enteric fermentation per cow) to generate national emissions for that activity. The degree of accuracy of the inventory will therefore be dependent on accurate collation of activity data (e.g. cattle population) and also the emissions associated per activity (called the EF). Inventories have a relatively low level of uncertainty for emissions associated with fossil fuel burning or industrial activity. Power consumption and fuel sales are relativity easy to measure and the amount of CO_2 generated from burning coal or oil is a generally constant value regardless of location. Likewise, mitigation is easy to capture. For example, if replacing fossil fuel burning for energy generation with wind energy, one can simply subtract those emissions.

However, agricultural inventories are more complex and have a much higher degree of associated uncertainty due to the biogenic nature of the emissions. For instance, N_2O emissions associated with nitrogen addition to soil will vary with soil type, the form of nitrogen applied and climatic factors such as precipitation and temperature. As a result, there is considerable temporal and spatial variation in emissions which is not reflected in the inventories. This results in considerable uncertainty in agricultural inventories. In addition, whilst mitigation that affects the *amount* of an activity can be counted (e.g. reduced fertiliser sales, cattle population), up to now any mitigation that affects the *emission factor* could not be captured (e.g. timing of fertiliser application, the use of chemical amendments to reduce methane and/or nitrous oxide and altering animal breed to reduce methane). This has led to a substantial portion of potential mitigation being unaccountable in national inventories (O'Brien et al., 2014). This was particularly true for nitrous oxide where IPCC Tier 1 default EF's were being used in Ireland. The move towards more disaggregated N_2O EF's has a) provided a more accurate analysis of the main sources on N2O emissions and b) allowed for mitigation to be included in national inventories (see Section 7.1.1.). The further refinement of these inventories, both in terms of more national specific EFs and better activity data (to account for timing of N application or provide better information on farm housing and storage facilities will be required in order to maximise the sector's mitigation potential, as all mitigation must be *measurable, reportable and verifiable* (MRV). Thus, further inventory refinement is crucial to meeting 2020 and 2030 emissions reduction targets as well as the long-term goal of carbon neutrality as envisaged under the National Mitigation Plan. This is true for all agricultural and land-use mitigation options. In addition, there must be a method that is independent and robust to collect the activity data in order to verify the activity.

Similar challenges arise in relation to soil C sequestration. This is due to the fact that the input rates of organic C into most soil systems is very small (< 1 t C ha^{-1} yr^{-1}) compared to the background SOC levels (typically 80 - 140 t C ha^{-1}). Whereas quantity and quality of input of carbon via litter fall and plant residues after harvest might be directly measurable, inputs via roots and rhizodeposition are more difficult to assess. The fundamental mechanisms involved are not yet fully understood and there is still no proper quantification of the release of organic and inorganic C compounds from roots or the assessment of seasonal dynamics (Smith et al., 2011). This low rate of change also requires that management practices are in place for a minimum of ten years before any statistically significant shift in soil organic carbon (SOC) is detectable (Smith et al., 2005). In addition, high resolution land- use and land management activity data is required in order to assess and verify the impact of land-use/ land management change on carbon sequestration. As a result, MRV for the impact of agricultural management to enhance soil carbon sinks is problematic. Teagasc are currently participating in an initiative sponsored by the FAO Livestock Environmental Assessment Programme (LEAP) to establish guidelines and systems to verify carbon stock changes in agricultural grasslands and also to design measures to incentivise the maintenance of soil C stocks.

A1.1. The Impact of Improved N_2O Inventories

As stated above, current IPCC Tier 1 EFs cannot capture a range of mitigation measures. There has been considerable research undertaken by the DAFM-funded Agricultural Greenhouse Gas Research Initiative for Ireland (AGRI-I, http:\\www.agri-i.ie) to produce national-specific Tier 2 factors that will dis-aggregate the N_2O EFs based on fertiliser type, dung and urine deposited N, timing of application and impact of soil type. Under this initiative, further refinement of methane and ammonia EFs is also being explored. However, this increased flexibility will bring its own challenges: the verification methods (i.e. the collation of activity data around timing of fertiliser spreading, fertiliser use by soil type and land parcel information for instance) will require considerable resourcing, particularly in terms of the National Farm Survey, the Ordnance Survey and farming stakeholders (see Section 4).

New disaggregated N_2O EFs, defined as % N_2O per kg N applied, have now been developed for mineral fertilisers and dung/urine deposition at pasture (Table A1.1). **The default emission factor (EF_1) for fertilisers was 1% regardless of N form or soil type (IPCC 2006, 2014b).** The EF for mineral fertilisers has been disaggregated between Calcium Ammonium Nitrate (CAN), Urea and stabilised urea formulations.

Grassland: N_2O emissions were, on average and across all sites, three times higher for CAN compared to other fertilisers and much more variable for CAN across soil types (Harty et al., 2016; Hyde et al., 2016; Carolan et al., In Prep; Higgins et al., In Prep; Krol et al., 2017). Novel fertiliser products containing urease inhibitors (to reduce ammonia) and nitrification inhibitors were also assessed (see Table A1.1). Soil type had a large impact on emissions with the EF (% N_2O per kg N applied) for WELL drained soils much lower compared to POOR drained soils as follows: CAN EF was 0.58% for a well-drained soil but 3.81% for a poorly drained soil). Urea products exhibited much lower variation across soil types (0.1% to 0.49%), Harty et al., 2016, Higgins et al., In prep, Hyde et al., 2016, Krol et al., 2017).

Table A1.1. Summary of fertiliser type direct N_2O emissions factors.

		Direct fertiliser type N_2O Emission Factor (%)				
Study	**Land-Use**	**CAN**	**Urea**	**Urea+ NBPT**	**Urea+NBPT + DCD**	**Urea+ DCD**
Harty et al. (2016)	Grassland	0.58-3.81	0.1-0.49	0.21-0.69	-0.05-0.27	-0.08-0.25
Hyde et al. (2016)	Grassland	2.15				
Krol et al. (2017)	Grassland	2.39	0.25	0.17	0.06	0.02
Higgins et al. (In Prep)	Grassland	0.44-3.81	0.3-0.49	0.25-0.43		
Mean EF	Grassland	1.85	0.25	0.4	0.11	0.11
Roche et al. (2016)	Arable	0.35	0.27	0.20	0.13	0.16

- Arable: N_2O emissions were lower than on grassland. There was no significant difference between CAN and other fertiliser types in terms of N_2O emissions, although the trend was for higher N_2O from CAN (Roche et al., 2016).

- Ammonia loss from urea was significantly higher than for CAN. When urea was treated with the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) urea ammonia loss was cut by 78%. Ammonia loss from urea treated with the urease inhibitor NBPT was not significantly different to CAN although there was a trend for lower emissions (Forrestal et al., 2016).

The EF for dung and urine deposited during grazing is defined as the Pasture, Range and Paddock (PRP) EF. **The default PRP emission factor (EF_3) was 2% regardless of N form or soil type effects (IPCC, 2006; 2014a).** The revised EFs averaged 0.31 and 1.18% for cattle dung and urine, respectively, with large variations across soil type both of which were considerably lower than the IPCC default value of 2% (Krol et al., 2016).

These revised factors have been assessed by the Environmental Protection Agency and are now incorporated into subsequent national inventories. Total N_2O emissions have reduced by 0.75 $MtCO_2$-e yr^{-1} as the contribution of PRP to total N_2O emissions decreases (Figure A1.1) and fertiliser becomes the dominant source of N_2O. As absolute emissions will be reduced, there will be a concomitant impact of inventory refinement on the emissions intensity of agricultural products. Indeed, it will result in a 7% reduction in the farm-based portion of the C footprint of beef and milk, driven mainly by a reduction in the PRP EF.

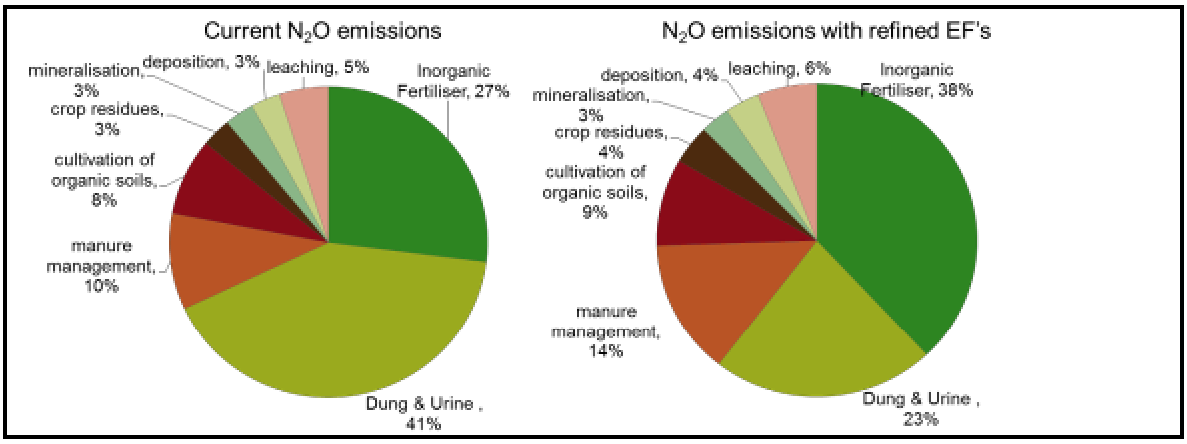

Figure A1.1: Impact of country-specific Tier 2 emission factors on national N_2O emissions.

A1.2. Accounting for Carbon Sinks & Sources under the Kyoto Protocol, EU Directives and the Paris Agreement

The rules governing the estimation of C sinks and sources have been discussed for a number of years. These rules directly impact on the amount of sequestered or emitted C that can be accounted for within national inventories.

Articles 3.3 and 3.4 of the Kyoto Protocol (KP) regulate accounting of removals and emissions from activities relating to LULUCF. As an overarching principle, only emissions that occur post-1990 and are a result of human intervention and additional to natural processes are accounted. Parties are not held responsible for emissions due natural disturbances beyond their sphere of influence, e.g. volcanic eruptions, nor do they receive credits for naturally occurring removals of C, e.g. sequestration due to marine sedimentation. Similarly, net sequestration is only deemed to occur where *additional* management indices a *verifiable* increase in C sequestration.

For the accounting of emissions and removals from the LULUCF categories (Article 3.3 and 3.4 Activities), three different accounting methods are used:

Gross-net accounting: The activities of KP Article 3.3, namely afforestation, reforestation and de-forestation are accounted using a gross-net approach. Net emissions from these activities result in the cancelation of Parties' Assigned Amount Units (AAUs, the mitigation target for an individual party), net removals result in the issuance of removal units (RMU). The principle behind gross-net accounting is that *all* emissions and removals from these activities should be accounted.

Reference level: For forest management during the second commitment period of the KP, a reference level is used. The reference level is based on emissions/removals arising from a projection of the impact of business as usual management of the forest, including the application of policies that were established before December 2009 (Iverson et al., 2014). Emissions or removals from a reference level, multiplied by the number of years in the commitment period, are subtracted from the net emissions or removals during the commitment period. Accountable net removals from forest management during the commitment period are capped at 3.5 per cent of a Party's GHG emissions in the reference year, excluding emissions/removals from LULUCF, multiplied by the number of years in the commitment period (2/CMP.7 Annex C). Net emissions are not capped.

The objective behind using a reference level is that emission/removal fluctuations resulting from normal planting and harvesting cycles as well as emissions from business as usual are to be ignored.

Net-net accounting: For emissions from non-forest activities under KP Article 3.4 (Cropland Management, Grazing Land Management, Revegetation and Wetland, Drainage and Rewetting), net-net accounting is used. Rules and guidelines relating to this are defined in 2/CMP.7 Annex C. Net-net accounting means that an activity's emissions during the reference year, multiplied by the number of years in the commitment period, are subtracted from that activity's emissions during the commitment period. As a result, only changes in emissions or removals relative to 1990 are accounted for while constant emissions or removals, irrespective of their amount, are budgeted as zero.

The principle behind using net-net accounting is that the status quo for the respective activities in the reference year is accepted and only improvements or deteriorations are accounted. This is important for the measure 'Water table manipulation of organic soils' whereby the draining and management of this land occurred pre-1990, but any re-wetting would be occurring post-1990. Therefore, only the decrease in total CO_2 emissions is counted towards national targets.

It should be noted that for the commitment period 2021-2030, it is proposed that forestry afforestation is calculated on a gross-net basis with a 20-year transition period, after which emissions and removals are counted relative to a reference level.

The proposed LULUCF regulation introduces *binding commitments* to GHG emission reduction in forestry and land use for all Member States, as well as related compliance rules for the 2021-2030 period (broken into two periods 2021-2025 and 2026-2030). This includes a no-debit rule whereby Member States have to offset *all deforestation* either by equivalent afforestation or by improving sustainable management of existing forests. Moreover, under this rule, the scope will be extended from only forests today to *all land uses* (and including wetlands by 2026).

When a Member State increases forest or agricultural land area, generating net removals beyond its commitment, it can use a limited number of these credits to comply with the Effort Sharing Regulation, or it can trade these removals with other Member States. If a Member State does not comply with the level of reduction set out for it in one of the five-year periods, the shortfall is deducted from the Effort Sharing Regulation allocations

Appendix 2: Individual Mitigation Measures

A2.1. Agricultural Mitigation

MEASURE 1: Improved Beef Liveweight Gain

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-215
Mitigation Mt CO_2 Eq:	0.061
Cost €M:	-13.1

The impact of beef genetics on terminal traits has recently been quantified (Quinton et al. 2018) with reductions in system EI of 0.021 kg CO_2-e/kg meat per breeding cow per year per

€ index, driven by increased meat production from improvements in carcass weight, conformation and fat. The current analysis evaluated scenarios of beef cattle production systems with different levels of lifetime average daily gain in the Grange Beef Systems Model (Crosson, 2008). This model facilitated the economic evaluation of lifetime average daily gain. Moreover, this model generated the outputs necessary to quantify GHG emissions (e.g. animal profile, feed budgets, manure management strategy). These outputs were applied in a beef systems GHG emissions model (BEEFGEM; Foley et al., 2011). This GHG model quantifies on-farm and total GHG emissions from beef cattle production systems using either LCA or IPCC methodologies.

Thus, national GHG emission profiles were generated for beef cattle production systems differing in lifetime average daily gain facilitating the calculation of the impact of this performance parameter on GHG emissions. The average system was based on Teagasc National Farm Survey data which consisted of 47.2 ha and was stocked with 30 spring-calving cows, with heifers finished at 26 months and steers at 30 months (Foley et al., 2011). A moderate increase in intensity was assessed with increased stocking rate to 2.2 LU ha^{-1}, a 14 kg N ha^{-1} increase in fertiliser and hence increased grass utilisation from 60-80%. This increased liveweight gain and thus reduced finishing times to 20 months (heifers) and 24 months (steers). Under the Teagasc Suckler Beef Roadmap (2016) there is a target to increase liveweight output from 422 kg ha^{-1} to 505 kg ha^{-1} and carcass output from 230 – 273 kg ha^{-1}. Improved average lifetime daily gain could result in increased absolute GHG emissions related to enteric fermentation, feed provision and manure management since the quantities of feed consumed and manure produced are greater.

However, GHG emissions per unit of beef produced are reduced by 17% from 23.1 to 19.7 kg CO_2-e carcass^{-1}, since the greater quantities of beef produced more than offset the increase in GHG emissions. However, beef production would have to be held at a certain level in order to realise absolute reductions. This is estimated at 61 kt CO_2-e but should be cost negative as there is a net cost reduction of €0.004 kg^{-1} carcass (Crosson et al., 2006). This increases beef profitability by €13 million and results in a savings of €215 per tCO_2-e. As with Measure 1, it should also be noted that government expenditure from the beef genomics scheme has not been included in these costs.

Key uncertainties are proportion of the national herd across which genetic improvement occurs, the extent to which finishing times are reduced and the improvement in liveweight gain and carcass conformation.

MEASURE 2: Improved Beef Maternal Traits

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-602
Mitigation Mt CO_2 Eq:	0.025
Cost €M:	-15.25

The impact of a range of index traits on system gross GHG (kg CO_2e / breeding cow / year / trait unit) and system GHG intensity (kg CO_2e / kg meat / breeding cow / year / trait unit) has been modelled (Quinton et al., 2018). This included the impact of trait alteration on feed consumption, methane production on per animal and per unit meat production basis as well as the impacts on animal numbers. Trait responses to index selection were predicted from linear regression for each index trait on their Maternal Replacement (MR) value. Regression coefficients were used to calculate responses in terms of both absolute greenhouse gas emissions and emissions intensity to index selection. The MRI Index was predicted to reduce system gross GHG emissions by 0.81 kg CO_2-e / breeding cow / year / € index, and system GHG emissions intensity by 0.0089 kg CO_2-e / kg meat / breeding cow / year / € index (Quinton et al., 2018). Reductions were mainly driven by improved health and survival, reduced mature cow maintenance feed requirements and shorter calving interval.

This analysis assumed a 65% adoption of the Beef Data and Genomics Programme (BDGP), where replacements are €30 superior in BDGP herds and a reduction in system EI of 0.009 kg CO_2-e/kg meat per breeding cow per year per € MR index with a current trend of €1.67 improvement in average MR indexyear^{-1} (Hely & Amer, 2016). This is projected to yield total cumulative cost benefits of €32 million after 10 years, rising to €58.2 million after 20 years (Hely & Amer, 2016). It should be noted that this analysis excludes the €300 million expenditure under the Beef Genomics Scheme. It should be noted that decreased production costs and/or increased production efficiency in terms of liveweight gain could result in increased absolute emissions if total herd numbers expand. This measure is sensitive (both in terms of emissions reduction and cost savings) to the proportion of the national herd across which genetic improvement occurs.

MEASURE 3: Improved Dairy Economic Breeding Index (EBI)

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-200
Mitigation Mt CO_2 Eq:	0.43
Cost €M:	**-**86

The abatement measure "improving genetic merit of the dairy herd" is based on O'Brien et al. (2011). GHG emissions from three strains of Holstein-Friesian cows differing in genetic merit (measured using the economic breeding index - EBI) were compared. The results of these field studies were included in the Moorepark Dairy System Model (Shalloo et al., 2004), which is used to operate a GHG model (O'Brien et al., 2011).

The GHG model results showed that increasing genetic merit via EBI reduced GHG emissions per unit of product by 2% for every €10 increase in EBI. This was because higher EBI cows had better fertility, which reduced emissions from non-milk producing animals and improved herd lifetime milk performance relative to lower EBI cows. Higher EBI cows improved a number of traits of economic importance simultaneously e.g. fertility, health and milk performance, whereas cows of lower genetic merit only improved single traits such as milk production. The EBI was established in 2001 and it is anticipated, based on the outcomes of this study, that increasing EBI will reduce emissions through a) Improving fertility, which reduces calving intervals and replacement rates, thus reducing enteric CH_4 emissions per unit of product; b) Increasing milk yield per unit of grazed grass and improving milk composition. This increases the efficiency of production, which decreases emissions (Martin et al., 2010). The Teagasc Dairy Roadmap projects that by 2025 average EBI will increase to €180/cow with a research herd target of €230/cow (Teagasc 2016). Milk delivered per farm will increase to over 570,000 litres, at almost 3.6% protein and 4.25% butterfat and the C footprint of milk production will be reduced by over 20%. This will result in a GHG reduction of 0.43 Mt CO_2-e yr^{-1}. Mitigation was based on:

- Earlier calving date to increase the proportion of grazed grass in the diet and reduce culling and replacement rates;

• Improved survival and health to reduce deaths and disease, which increases efficiency and reduces emissions.

MEASURE 4: Extended Grazing

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-96
Mitigation Mt CO_2 Eq:	0.066
Cost €M:	-6.3

The measure "grazing season length" quantifies the impact of changing grazing season length on the GHG emissions from production systems that either require improved drainage or could benefit from on-off grazing. This area was calculated from the area of soils associated with impeded drainage (O'Sullivan et al., 2015).

Increasing the proportion of grazed grass in the feed budget and reducing the proportion of grass silage in the diet improves feed digestibility and quality. Improving the digestibility and quality of feed consumed reduces CH_4 emissions because of improvements in animal productivity as well as reductions in the proportion of dietary energy lost as CH_4 (Martin et al., 2010). This latter point may result from a reduction in the fibre content of the sward (i.e., an increased proportion of leaf at the expense of stem and dead material in the high-quality sward) causing an increased proportion of propionate in rumen volatile fatty acids. Propionate acts as a sink for hydrogen and therefore reduces the amount available for CH_4 synthesis. It is widely accepted that pasture is a higher quality feed than grass silage and therefore the above effect is compounded, leading to a reduction in emissions through extending the grazing season.

Dairy: The abatement measure "extended grazing season" is based on studies by Lovett et al. (2008), which compared two sites with contrasting soil types and climatic conditions: a) Kilmaley receiving an average annual rainfall of 1,600 mm with an impermeable soil (infiltration rate of 0.5 mm hr^{-1}) and b) Moorepark had an average annual rainfall of 1,000 with a highly permeable soil (10 mm hr^{-1}). Both systems were optimised resulting in Moorepark having a grazing season length of 250 days per year with the corresponding Kilmaley figure of 149 days per year. The analysis showed that for every one day increase in the grazing season, the IPCC and LCA emissions reduced on average by 0.14% and 0.17% per unit of milk and reduced costs to the extent of €3.24 cow^{-1} (Shalloo et al., 2004). This measure interacts with the measure "manure management", since reducing the period manure is stored while cows are grazing will reduce CH_4 emissions in addition to the emissions reduction that occurs by extending the grazing season.

Beef: Animal performance benefits are not considered because compensatory growth for later turned out cattle is assumed to offset temporary performance gains for earlier turned out cattle (Kyne et al., 2001). The analysis was conducted by evaluating scenarios of beef cattle production systems with different grazing season lengths in the Grange Beef Systems Model (Crosson et al., 2006; Crosson, 2008). This generated the outputs necessary to quantify GHG emissions (e.g. animal profile, feed budgets, manure management strategy). These outputs were applied in a beef systems GHG emissions model (BEEFGEM; Foley et al., 2011). This GHG model quantifies on-farm and total GHG emissions from beef cattle production systems using IPCC 2014 methodologies and inputs these into an IPCC national inventory model. Thus, GHG emission profiles were generated for beef cattle production systems with different grazing season lengths facilitating the calculation of the impact of this parameter on GHG emissions.

In summary, emissions are reduced due to: a) reduced slurry CH_4 and N_2O emissions from storage since quantities stored will be lower, b) higher pasture range and paddock emissions from direct deposition since time spent grazing will be greater (but these are 42% reduced due to new N_2O EFs), c) lower enteric fermentation emissions since the digestibility of grazed forages is greater than that of conserved forages and thus, the EF used is lower and d) fuel emissions are lower as a result of reduced forage harvesting and feeding out requirements.

The measure was assessed on 20% of grassland area (30% is deemed to be 'impeded drainage). This results in a reduced emissions intensity of 0.025 kg CO_2-e carcass^{-1} d^{-1} and a lower relative cost of €0.006 per day extra of grazing for suckler beef systems.

MEASURE 5: Nitrogen-Use Efficiency (NUE)

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-84.9
Mitigation Mt CO_2 Eq:	0.112
Cost €M:	-9.51

Nitrogen use efficiency is based on fertiliser N use due to improved nutrient management planning (NMP) and particularly the optimisation of soil pH. Soils in Ireland are naturally acidic and require applications of lime (usually ground limestone ($CaCO_3$)) in order to neutralise this acidity and restore a more favourable soil pH for crop growth, nutrient release and soil quality. The application of lime as a soil conditioner and specifically to neutralise soil acidity and raise pH to an agronomic optimum level confers many benefits in terms of crop production, soil nutrient availability and fertiliser efficiency to name but a few. While targeting a similar grass yield, by increasing the soil pH from 5.5 to 6.3 with lime application the N fertiliser required could be reduced by up to 70kg N ha^{-1} yr^{-1} (Culleton et al., 1999). Additionally, increasing the soil pH from 5.4 to 6.3 with lime application led to on average 5.3 kg ha^{-1} additional P uptake by the grass sward in the following 3 growing seasons (Fox et al., 2015). It was assumed that of the two-thirds of grassland soil at sub-optimal pH, one third of this area (429,000 ha) would be brought to optimal pH conditions with the application of 7.5 t lime ha^{-1}. This would release up to 30,000 t N by 2030, reducing direct and indirect N_2O emissions by 119.6 kt CO_2-e. However, there would also be CO_2 emission associated with the mineralisation of C from lime (EF=0.12 of applied lime) resulting in 6.8 kt CO_2-e. Costs include a one year in three lime application of 7.5 t ha^{-1} at €22 per tonne while savings were via avoided N application (70 kg N ha^{-1} yr^{-1} at €1.18 per kg N) and P (5.3 kg P ha^{-1} yr^{-1} at €2.62 per hectare). The net savings from this measure were calculated at 23.2 million per annum. However, as this measure interacts with C sequestration in grasslands, the savings were allocated between the two measures based on the total level of mitigation obtained by each measure. As a result, 60% of the mitigation savings were allocated to the N_2O savings from this measure – €13.95 million or €124 per tonne CO_2-e.

This measure is sensitive to uptake rate and the type of fertiliser being replaced with mitigation ranging from 53 ktCO_2-e (assuming that all fertiliser replaced was a urea product) to 205 ktCO_2-e (assuming full CAN replacement with full uptake occurring in 2021). Cost savings, using similar assumptions range from €8.5 million to €25.6 million.

MEASURE 6: Improved Animal Health

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-46
Mitigation Mt CO_2 Eq:	0.147
Cost €M:	-6.76

In order to quantify the mitigation, the values for key production parameters (replacement rates, fertility rates, milk yield, mortality etc.) were estimated for two situations: baseline and healthy (ADAS 2015). In this study, the productivity parameters for the top eight diseases and treatment were used to generate production parameter values and emissions estimates for dairy cattle and suckler cows using an LCA analysis. The reference point for disease impact was a 'healthy animal', i.e. absence of all disease. The difference in productivity between the healthy animal and that of a diseased animal was converted to CO_2-e per unit output to represent the full impact of each condition. The extent to which the national herd average could be moved from the baseline value to the healthy value was assumed to be 20%.

Costs were variable depending on the disease being treated and the mitigation measure (ADAS 2015 Table A2.1). In terms of dairy, marginal costs varied from -€197 t^{-1} CO_2-e abated for pneumonia vaccination to the use of slat mats to reduce lameness (€820 t^{-1} CO_2-e). Beef costs varied from €721 t^{-1} CO_2-e for colostrum intake/management to reduce pneumonia to altering stocking rates and buying policy for pneumonia (€416 t^{-1} CO_2-e).

The mean marginal costs across these measures were observed to be cost effective with marginal costs calculated at -€46 t^{-1} CO_2-e abated. The measure reduces GHG per kg product by reducing the need for replacements and an increase in overall production.

Table A2.1: Impact of disease on percentage increase in GHG emission intensity for dairy and beef (adapted from ADAS 2015).

	Disease	**% Increase in CO_2e above healthy**
Dairy	Johnes	23
	Salmonella	19
	BVD	18.5
	Infertility	17
	Liver Fluke	10.5
	IBR	8
	Lameness	7.5
	Mastitis	7
Beef	BVD	130
	Johnes	40
	IBR	20
	Infertility	20
	Salmonella	18
	Liver Fluke	10
	Diarrhoea	4
	Pneumonia	4

MEASURE 7: Increase Use of Sexed Semen

Nature of Measure: Production Efficiency

Cost € per t/ CO_2 Eq: 27.3

Mitigation Mt CO_2 Eq: 0.024

Cost €M: 0.66

Sexed semen is a process where sperm is differentiated into those containing Y and X chromosomes. This semen is then used for artificial insemination (AI), leading to a majority of calves of a single sex. For dairy systems, this technique increases the proportion of pure female dairy (i.e. dairy x dairy) thus reducing the number of male pure dairy calves and increasing the number of dairy x beef calves (of both sexes) for rearing as beef animals (Hutchinson et al., 2013). Increasing the number of dairy x beef calves means that less suckler cows are required to produce the same total beef output, thereby reducing the total emissions and the emissions per kg of beef produced. The scenario analysed sexed semen in heifers and a targeted group of cows, with conventional semen in the remainder of conventional beef semen used for the second AI. Herd size increased from 100-300 cows in this scenario with 94% of conventional conception rate assumed (Murphy et al., 2016). Greenhouse gas savings were made due to a reduction in pure male calves that would otherwise occur, thereby increasing the proportion of beef arising from the dairy herd and reducing the suckler (+ followers) population. Linear uptake of this measure equates to a reduction of 0.024 Mt CO_2-e. However, it is unclear if the uptake of sexed semen will be widespread. This is due to a number of factors including a) the current cost of straws (cost of sexed semen is €38 compared to €18 for conventional semen); b) the use of (particularly frozen) sexed semen can reduce conception rates substantially and c) rapid expansion of dairy herds could place strains in terms of facilities or labour and leave farmers more sensitive to milk price fluctuation.

MEASURE 8: Inclusion of Clover in Pasture Swards

Nature of Measure:	Production Efficiency
Cost € per t/ CO_2 Eq:	-6.9
Mitigation Mt CO_2 Eq:	0.069
Cost €M:	-0.48

Legumes (clover) were assumed to fix on average 80 kg N ha^{-1} yr^{-1} (Burchill et al., 2015), with 25% uptake beef farms and 15% uptake by dairy farmers (principally smaller dairy farms) by 2030. Greenhouse gas emission reductions of 69 kt CO_2-e were achieved from avoided fertiliser emissions (direct and indirect N_2O). Re-establishment of clover was assumed to be performed by broadcast of seed in order to reduce both cost and impacts on soil organic carbon. The cost associated with this measure includes the cost of clover establishment (€12 per kg of seed sown, with 5 kg sown per ha) with savings associated with reduction in 17,400 tonnes N applied at €1.18 per kg N. The cost savings were shared with C sequestration from grasslands, (see below) as grass/clover pastures can sequester more C compared to *Lolium*-only pastures with a similar N fertilisation rate (Bannink & Lanigan, 2013).

MEASURE 9: Switching Fertiliser Formulation from CAN to Protected Urea

Nature of Measure:	Reducing N emissions
Cost € per t/ CO_2 Eq:	8.31
Mitigation Mt CO_2 Eq:	0.521
Cost €M:	4.2

Altered fertiliser formulation offered the single largest abatement measure with mean N_2O reductions of 0.52 Mt CO_2-e yr^{-1} between 2021 and 2030 and a maximum mitigation potential of 0.75 Mt CO_2-e yr^{-1} based on a 50% replacement of CAN (either straight or in compounds) *applied to grassland* with protected urea products and is based on a shift in the mean N_2O EF_1 from 1.49% for CAN to 0.4% for protected urea i.e. urea coated with a urease inhibitor such as NBPT (Harty et al., 2016, Table A1.1). The mitigation potential was assessed using the Tier 2 IPCC calculation methodology (IPCC, 2014b) and therefore includes the calculation of N_2O emissions from indirect sources and CO_2 emissions from urea use.

Currently, CAN accounts for about 84% of the straight N market (Forrestal et al., 2017). Protected urea was not applied to arable land in these simulations as relative to grassland, emissions from free-draining arable soils are low and less variable (Forrestal et al., 2016) with only small differences in the N_2O emission factor associated with fertiliser type on free- draining arable soils (Roche et al., 2016) (EF = 0.35%) and where N_2O loss is dominated by nitrification processes.

As commercially available urease stabiliser-coated urea fertiliser retails at a similar price to CAN (€1.12 per kg N), the cost of this measure reflected the need to replace straight urea (€0.86 per kg N) with urea + NBPT, as ammonia emissions (and indirect N_2O from N deposition) are required to reduce by 5% by 2030. The mean total cost over the 2021-2030 period at these prices is €4.3 million or €8.31 per tonne CO_2-e abated.

Sensitivity associated with the abatement potential of this measure was mainly associated with uptake rate. If the measure were introduced immediately at the full rate of uptake, the mitigation potential would increase to 0.97 Mt CO_2-e.

MEASURE 10: Reduced Crude Protein in Pig Diets

Nature of Measure:	Reducing N_2O emissions
Cost € per t/ CO_2 Eq:	12
Mitigation Mt CO_2 Eq:	0.051
Cost €M:	0.61

The reductions in GHG associated with feeding pigs' diets with reduced crude protein (CP) were based on a 4% reduction in dietary protein. These strategies have the advantage that they can reduce manure emissions from both storage and upon application to the land. Reducing CP content can reduce both N excreted and the proportion of N in urine and lead to a reduction in ammonia and N_2O emissions (Lynch et al., 2008; Meade et al., 2011). Lowering CP in pastoral systems is difficult. In beef systems, the scope was considered to be small for two reasons. Firstly, most cattle are managed extensively with low levels of supplementation, so dietary manipulation to reduce CP is limited. Secondly, the level of N application is very low, approximately 40 kg per hectare annually, so the capacity to reduce N fertilizer (in order to reduce CP) is also limited. Only a minority of cattle are finished on high concentrate indoor systems and in these instances, CP levels are already low (<12%). It might be argued that CP in concentrate for weanling/store cattle (i.e. young, growing animals) could be reduced slightly (typically rations are ~14-16%) but given the highly variable nature of grass silage quality, higher levels than those that are strictly necessary are justified. As a result, the measure was considered to be mainly applicable to pigs. A 10% reduction in N_2O emissions per 1% CP reduction was assumed (Meade et al., 2011). In addition, there was a reduction in indirect N_2O associated with reduced ammonia emissions. The cost of the diet manipulations was assumed in the range of €-10 to €10 per 1000 kg of feed, depending on market conditions for feed ingredients and the cost of the synthetic amino acids. As a result, the costs associated with CP supplementation could be cost-neutral depending on the relative costs of soya bean meal and supplemental amino acids.

MEASURE 11: Draining Wet Mineral Soils

Nature of Measure:	Reducing N_2O emissions
Cost € per t/ CO_2 Eq:	16.2
Mitigation Mt CO_2 Eq:	0.197
Cost €M:	6.1

Drainage of wet mineral soils was calculated to be based on a reduction in the N_2O EF. According to data from the Irish Soil Information System (SIS), one-third of Irish land area can be classified as poorly draining. This change in the EF value was based on modelled outputs using the DeNitrification Decomposition model (Li et al., 2012) and validated based on the range of EFs generated by Harty et al. (2016) and Krol et al. (2016) for poor, medium and well-drained soils. This resulted in a mean reduction in N_2O emissions of 58% and 40% for CAN and urine applied to grassland respectively. Assuming that one-third of this area (i.e. 10% of total grassland area) was drained by 2030, the total N_2O would reduce by 0.197 $MtCO_2$-e yr^{-1} (based on linear uptake from 2021-30) up to a maximum of 0.318 $MtCO_2$-e yr^{-1}.

Costs were based on the installation of 33% shallow mole drains, 33% gravel mole drains and 33% at 1-1.5 m apart and collector drains 20 m apart and deep drains at 30 m apart with subsoiling. When costs for re-seeding, fuel and labour were included, this resulted in total costs of €5,285 per hectare. Assuming a base case farm of 40 ha and 28 c l^{-1} increased dairy profitability for shallow, gravel mole and deep drains were estimated at €7324, €5033 and
€4201 (or €183, €126 and €105 per hectare) assuming a 20% increase in grass growth, due to increases in stocking rate and reduced cost incurred due to reduced feed purchase (Teagasc 2013). While increased grass growth (20% assumed) also reduced feed costs, this did not offset the cost of drainage, which was based on 40 ha land and a beef carcass price of €4.25 per kg. Profitability was estimated to be -46%, -84% and -97% for shallow, gravel mole and deep drains respectively.

Drainage was very cost sensitive to the a) use of gravel moles versus shallow moles (costs ranging from €125 – 1400 per ha), b) frequency/spacing of collector drains (between €800 and 3,200 per ha based on 60 m and 20 m spacing respectively) and c) the duration that the drains are operational (Teagasc 2013). Drainage of land on beef farms was particularly sensitive to fluctuation in beef price and assumptions on increases grass growth, with profitability of drainage only occurring at 30% increase in grass growth and €4.75 per kg carcass.

MEASURE 12: Slurry Chemical Amendments

Nature of Measure:	Reducing nitrogen and methane emissions
Cost € per t/ CO_2 Eq:	49.3
Mitigation Mt CO_2 Eq:	0.027
Cost €M:	1.35

The amendment of manures and slurries using compounds such as alum, ferric chloride or polyaluminium chloride has been shown to sequester phosphorus, reduce ammonia emissions on landspreading and reduce methane and ammonia during storage (Brennan et al., 2015). It was projected that 20% of slurry (mainly slurry in external stores) was treated at the following stoichiometric rates determined from Brennan et al. (2011) alum 1.11:1 (Al:TP); aluminium chloride ($AlCl_3$) or PAC 0.93:1 (Al:TP); $FeCl_2$ 2:1 (Fe:TP). This was projected to reduce ammonia by 70% and methane emissions by 80% over the storage period. A 20% uptake was assumed, mainly from dairy and pig farmers with external stores. This resulted in a mean reduction of 8.6 kt CO_2-e from methane during storage as well as 18.7 kt CO_2-e from indirect N_2O that arises from ammonia deposition. Amendment of manures with alum has also been shown to reduce P loss (Fenton et al. 2011). The reduction in litter pH following application may also causes pathogen numbers to decrease (Moore et al. 2000). The cost of FeCl and alum ranged from €200 – €350 per tonne. This measure is primarily an ammonia abatement measure.

MEASURE 13: Adding Lipids/Fatty Acids to Dairy Diets

Nature of Measure:	Reducing methane emissions
Cost € per t/ CO_2 Eq:	76.1
Mitigation Mt CO_2 Eq:	0.035
Cost €M:	2.7

Increasing the unsaturated fatty acid content of ruminant feed reduces enteric CH_4 emissions by a) inhibiting rumen microbial growth, b) acting as a hydrogen sink and c) increasing the proportion of feed components which are digested in the intestine rather than the rumen (Johnson and Johnson, 1995; Martin et al., 2010). Due to the fact that fatty acids could not be fed during grazing, it was considered most appropriate to feed to dairy cows and heifers. A meta-analysis has shown that for a 3% DM% fat supplementation, directly replacing concentrate in the diet, a 10.3% methane reduction was observed (Mc Bride et al., 2015). Costs were due to the replacement of concentrate with a high fat source, such as oilseed rape and are dependent on the cost of the high fat source relative to the replaced source. Oil sources such as rapeseed and linseed are expensive at between €300 – 370 t^{-1}. If oilseed replaces a standard concentrate, the cost of diet change is €23 t DM^{-1} or €45 per dairy cow.

MEASURE 14: Low-Emission Slurry Spreading

Nature of Measure:	Reducing nitrogen and methane emissions
Cost € per t/ CO_2 Eq:	187
Mitigation Mt CO_2 Eq:	0.117
Cost €M:	15.7

Reductions in N_2O from storage and landspreading were almost exclusively from reduced indirect N_2O emissions associated with reduced ammonia emissions. These application techniques reduce ammonia losses and also increase the nitrogen fertilizer replacement value (NFRV) of slurry, and therefore reduce the total fertilizer N inputs and associated reactive N emissions from soil. This occurs by reducing the surface area exposed for volatilisation. Trailing shoe is more effective at reducing volatilisation, as the slurry is placed directly on the soil beneath the sward. Some studies have suggested that this practice leads to increases in direct N_2O emissions, but Irish studies (Meade et al., 2011; Bourdin et al., 2014; Cahalan et al., 2014) on bandspreading and trailing shoe application to pasture and arable land have not detected any significant increase. It should be noted that there was no statistical difference in the NH_3 emissions associated with splashplate application of slurry in comparison with trailing shoe/trailing hose application during spring and late autumn in Irish studies, with observed reduction in volatilisation of 60% (summer) and 13% (spring, not significant) compared to splashplate application (Dowling et al., 2010; Bourdin et al., 2014). Similarly, bandspreading was observed to reduce emissions by 40% (summer) and 10% (spring, not significant). Therefore, a shift of slurry application to spring will, *per se*, reduce the efficacy of alternative techniques compared to trailing shoe in terms of the total amount of ammonia abated when techniques are used in combination.

A 50% limit on the slurry applied by alternative techniques was assumed as agricultural contractors are estimated to account for approximately 50% of slurry spread in Ireland (Hennessy et al., 2011). This constraint was assumed due to the high cost of the technology, which will primarily restrict adoption to agricultural contractors. In essence, the volume of slurry applied annually with each machine has a large effect on the gross cost of ammonia abatement. Farmer-owned machines will typically spread 500 – 2000 m^3 yr^{-1} slurry, while contractors will spread 5000 – 20000 m^3 yr^{-1} slurry (Lalor, 2012). As a result, the marginal abatement costs will increase approximately ten-fold for farmer-owned machines. Conversely, if 100% of slurry was spread by trailing shoe, the costs would increase from €182 per tCO_2e abated to €1620 per tCO_2e, as individual farmers would have to buy their own machines. The relative cost of this measure is €1.32 per m^3 slurry spread and consists of machinery purchase and increased fuel and labour use minus increase in NFRV. While this measure is extremely costly in terms of GHGs, it is included as it is cost-effective in terms of ammonia abatement (between €3.80 and €5.21 per kg NH_3 abated, see Lalor 2012, Lanigan et al., unpublished).

A2.2. Land-use Mitigation

MEASURE 15: Improved Grassland Management

Nature of Measure:	Better management of 450,000 ha of grassland (increased time to reseeding, increase in legumes, less frequent use of heavy machinery, long term pasture management plans)
Cost € per t/ CO_2 Eq:	-41
Mitigation Mt CO_2 Eq:	0.262
Cost €M:	-10.7

Soil quality in grasslands could be improved by achieving a 'right' balance between C and N inputs to soils. A combination of agricultural practices, which promote the formation of stable soil aggregates, will improve soil quality and sustainability. Some management options include:

1. In permanent grasslands (> 5 yrs) a key step is to improve either organic or inorganic fertiliser management. A first step would be to combine liming treatments with either organic and/or inorganic nutrient fertilization (N, P, K, Mg etc.). In terms of temporary sown grasslands (< 5yrs) and renovation via ploughing, a key step is to increase the time between re-seeding to at least five years, as this will contribute to an organic matter build-up through reduced tillage events or to direct drill in place of inversion ploughing.
2. Increasing the abundance of legume species in some grass swards can improve sequestration, forage quality, and reduce inorganic N inputs. In combination with legumes, a more diverse vegetation cover (>4 species) can make grasslands more resilient in terms of climate change, and may provide both a better forage quality and organic matter input.
3. A third step is to reduce frequency of use of heavy machinery, which could cause high soil compaction and thus 'reducing' pore space available in the soil matrix, necessary to transport and accumulate extra C (via soil climate, macro fauna, earthworms, microbes, etc.). Animal grazing is preferable compared to silage/hay production, due to the nutrient recycling of animals and the reduction in work (25 to 40% of ingested

herbage is returned to the pasture in excreta).

4. Finally, the development of pasture management plans perhaps around a 5 to 7 year cycle where a combination of different practices (liming, nutrients, grazing, reseeding) guarantee balanced applications of C and N to soils under moderate (soil) disturbance (avoid high animal stock densities and intensive mowing). A soil monitoring program including analyses of soil C and N content, soil bulk density and pH should be put in place and run every 2- to 3 years.

Measured values for Irish grasslands range between a gross sink of 1 t C ha^{-1} yr^{-1} and a source of -0.4 t C ha^{-1} yr^{-1} with management increasing net-net sequestration by 0.55 t CO_2 ha^{-1} yr^{-1} (Soussana et al., 2007; Gottschalk et al., 2007; Torres-Sallan et al., 2017). Annual estimates are confounded by considerable inter-annual variation in values of Net Ecosystem Productivity and this variation is driven mainly by soil and climatic factors (Torres-Sallan et al., 2017). If 450,000 ha are optimally managed, this will result in sequestration of 0.262 Mt CO_2-e. Costs include extra lime, clover seed, fuel usage and farmer time, offset with higher grass yields. Thus, the measure interacts with 'improved NUE' and 'inclusion of clover' and the overall cost savings has been allocated between N_2O reduction and C sequestration based on the proportion of GHG mitigation achieved.

MEASURE 16: Water Table Management of Peaty Agricultural Grassland Soils

Nature of Measure:	Rewetting of 40,000 ha of organic grassland soils
Cost € per t/ CO_2 Eq:	10.9
Sequestration Mt CO_2 Eq:	0.44
Cost €M:	4.84

A significant part of organic soils in Ireland are drained for agriculture (Duffy et al., 2018). While new drainage operations on cropland or grassland require screening by the Irish DAFM if they exceed 15 hectares, regulations pertain only to new drainage work and not to the maintenance of existing drainage systems. First state supported national drainage schemes date back to the end of the 19th century and the majority of agricultural drainage works have been carried out prior to 1990 (Burdon, 1986) when the regulations mentioned above did not exist. We therefore assume that most farmland on poorly draining carbon rich soils has been artificially drained at some stage in the past.

Ireland has elected to account for cropland management and grazing land management in the second accounting period of the Kyoto Protocol. As drainage systems are considered to have been installed before the reference year 1990, under the net-net accounting Ireland is not accounting for on-going emissions while receiving carbon credits where original drainage has been reduced with a decline of the total area of agricultural land use (DAFM, 2015). In order to identify the areas with drained organic (histic) soils, a Land-Use Map (O'Sullivan et al., 2015) was combined with Soil Information System data

(Paul et al., 2017). For calculating emissions from drained histic soils we used the generic (Tier 1) values provided by the IPCC (2014c) Wetland Supplement. We included direct CO_2 emissions, offsite CO_2 emissions from dissolved organic carbon (DOC) in drainage water, CH_4 emissions from both soils and open drainage ditches, as well as direct N_2O emissions from soils and take away the CH_4 emissions associated with re-wetting (Table A2.3).

Table A2.3: Difference of emissions from drained and rewetted organic soils Mg CO_2-e $ha^{-1} yr^{-1}$.

	Emissions Drained	**Emissions Rewetted**	**Δ Emissions**
Land use	**[Mg CO_2e ha^{-1}*yr^{-1}]**		
Cropland, nutrient poor	37.6	3.1	34.5
Cropland, nutrient rich	37.6	9.9	27.7
Grassland, nutrient-poor, shallow drained	23.3	3.1	20.2
Grassland, nutrient-poor, deep drained	24.1	3.1	21.0
Grassland, nutrient-rich, shallow-drained	16.7	9.9	6.8
Grassland, nutrient-rich, deep-drained	29.2	9.9	19.3

A total of 918,000 ha of histic soils were under agricultural land use within the selected association and 31,000 ha that constituted minor proportions of other associations. Because only 15% of other pastures were assumed to be drained, the total area of drained histic soils was 370,000 ha. While croplands have the highest per hectare emissions, the emissions profile is dominated by emissions from managed grassland sites. 16% of emissions (1.4 Mt CO_2-e) are generated from drained sites within protected areas. If drainage was stopped completely and natural water table conditions were restored, 40,000 ha of re-wetted grassland **would result in emissions savings of 0.44 Mt CO_2-e yr^{-1}.** Alternatively, 65,000 ha nutrient rich, managed grasslands could be converted from deep drained to shallow drained state, resulting in the same level of sequestration. Focussing on emission hotspots by targeting only cropland areas would result in savings of 0.13 Mt CO_2-e yr^{-1}. However, this would come at the cost of total cessation of tillage production on this land and has not been included in the final analysis.

The cost was estimated for extensive beef systems (1 cow per hectare) as €1.54 ha^{-1} per dry day, indicating potential annual income losses of up to €190 ha^{-1}. The costs of €4.84 M associated are costs of reduced grass growth and increased concentrate requirement giving a total abatement cost of €10.87 per tonne CO_2 abated.

The main parameters driving sensitivity around the mitigation potential of the measure apart from total hectares drained were water table height and rate of uptake. If 40,000 hectares were converted from deep to shallow drains, 0.275 Mt CO_2-e would be abated compared to 0.44 Mt CO_2-e if the 40,000 ha were converted in 2021. In addition, a large portion of previously drained grassland on organic soils may already be re-wetted as drains on marginal land have fallen into disrepair. This would result reduced reported CO_2 loss from a much larger area at little cost (the cost of mapping these areas and verifying emission reductions).

MEASURE 17: Forestry

Nature of Measure:	Afforestation at a rate of 7,000 ha per year
Cost € per t/ CO_2 Eq:	45
Mitigation Mt CO_2 Eq:	2.1
Cost €M:	97.4

Forest Management is the only LULUCF activity for which a reference level has been adopted for accounting. This is justified by the long life-cycles in forest operations, the high amount of both emissions and removals from this activity and the strong influence of legacy effects such a forest structure and age classes. Using gross-net accounting would lead to very strong fluctuations in annual GHG budgets of forest-rich Parties, while using a reference year would favour those Parties where a high share of trees had been harvested shortly before the respective date. However, the design of forest reference levels goes beyond this and also accounts for effect of national forest policies established before December 2009. Under these amended rules, a large portion of the post 1990 forestry sink as previously reported under gross-net rules is now to be reported under forestry management rules, with the forestry sink measured using a 20 year window (i.e. from 2008 onwards, Figure A2.2). This results in a mean annual sink of 2.1 Mt CO_2-e yr^{-1} on current replanting rates of 7000 ha yr^{-1}. Net costs comprising replanting, changes in land price and management costs minus income from clear-felling, are €103 M, resulting in a €46 per tonne CO_2-e abated. In this analysis, the afforestation rate from 2021-2030 has been held static at 7,000 ha per annum. This is due to considerable barriers to uptake within the farming community. Ryan & Donoghue (2016) analysed farmer attitudes to afforestation, and showed that whilst soil type, agricultural market income and level of subsidies had an impact on uptake rates, 84% of farmers surveyed would not consider planting in the future, regardless of the financial incentives offered. To help achieve current Government targets of 18% forest cover (DAFM 2014), an urgent acceleration of the afforestation programme is necessary, requiring the planting of 490,000 ha of new forests by 2046. Farrelly & Gallagher (2015) identified that in order to meet any national afforestation targets it may be prudent to focus on opportunities for afforestation on the 1.3 M ha of marginal agricultural grassland in the first instance.

This measure is sensitive to a) replanting rates and b) the type of forestry planted. If a larger proportion of broadleaves are planted, the annual afforestation rate would decrease as broadleaf trees have a sequestration rate of less than half that of Sitka spruce. However, the stands also take longer to reach maturity and canopy closure. As a result, the 20 year time window would increase considerably for these species.

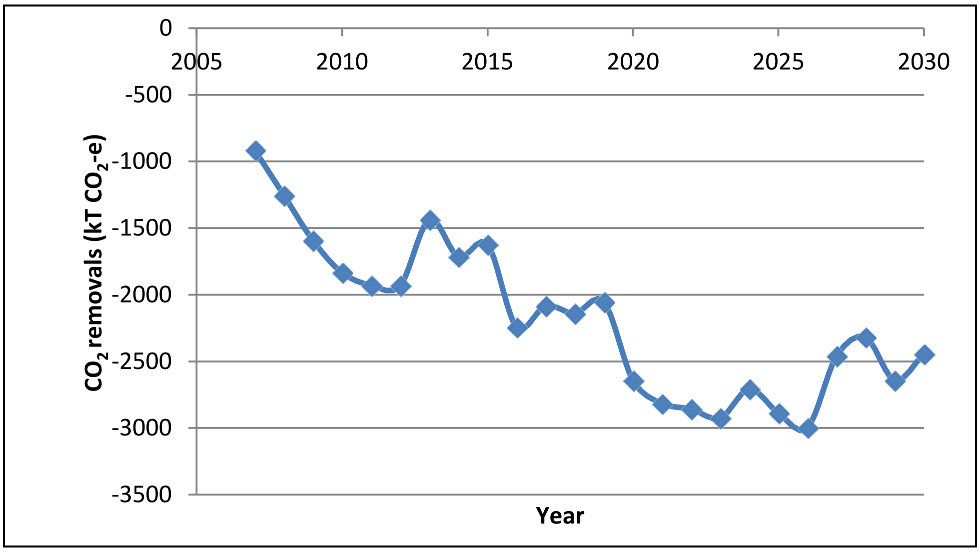

Figure A2.2: Annual profile of CO_2 sequestration from forestry.

MEASURE 18: Inclusion of Cover Crops in Tillage

Nature of Measure:	Better management of tillage land (winter cover)
Cost € per t/ CO_2 Eq:	86
Sequestration Mt CO_2 Eq:	0.108
Cost €M:	9.3

The principal loss pathway for carbon within a tillage system is the extended fallow period, during which time there is no uptake of CO_2, whilst ploughing affects the recalcitrant C pools (Willems et al., 2011). Cover crops are traditionally used to reduce leached N emissions to groundwater during the fallow period. However, winter cover has also been observed to reduce net soil CO_2 emissions due to the fact that there is net photosynthetic uptake of CO_2 by the cover crop (Ceschia et al., 2010). The principle crop used is mustard (*Sinepsis alba*), due to the fact that it is fast growing, has good N uptake characteristics and reduces nitrate leaching in Ireland (Premrov et al., 2014). The net change in annual GHG fluxes is 1.33 t CO_2 ha^{-1} yr^{-1}. This is due to both a reduction in C loss (0.73 t CO_2 ha^{-1}

yr^{-1}, see Davis et al., 2010) and a reduction in indirect N_2O losses associated with reductions in leached N (0.49 t CO_2-e ha^{-1} yr^{-1}, Kindler et al., 2012). The area available is limited to the spring barley area of 161,000 ha (mean projected spring crop area by 2021-2030). This delivers a mean mitigation of 0.108 Mt CO_2-e yr^{-1}. Costs involved include seed (15 kg ha^{-1} at €60 ha^{-1}, fuel and ground preparation (€90 ha^{-1}) a saving of €40 kg N ha^{-1} yr^{-1} at 1.12 kg^{-1} N saved (Kindler et al., 2011) giving a total cost of €9.3 million and €86 per tonne CO_2-e abated.

MEASURE 19: Inclusion of Straw Incorporation in Tillage

Nature of Measure:	More organic C inputs into the soil as straw
Cost € per t/ CO_2 Eq:	279
Sequestration Mt CO_2 Eq:	0.0605
Cost €M:	16.9

Straw incorporation increases SOC, as organic matter is directly inputted back into the soil. For every 4 tonnes of straw incorporated over 15-20 years, a 7-17% increase in SOC (top 15 cm only) has been observed (depending on whether reduced tillage was also applied, (see Powlson et al., 2008; van Groenigen et al., 2011). Manure inputs will also build SOC stocks, particularly farmyard manure (Jenkinson & Rayner, 1977). This results in net annual sequestration of 1.2 t CO_2 ha^{-1}. If 25% of the tillage area re-incorporated straw, that would offset 0.109 Mt CO_2-e yr^{-1} at a cost of €101 t^{-1} CO_2-e abated. This measure is expensive due to the high price of straw (circa €35 t^{-1}) and low N replacement value (circa 20 kg N ha^{-1}).

A2.3 Energy Mitigation

MEASURE 20: Increased Farm Energy Efficiency

Nature of Measure:	Deployment of plate coolers, variable speed drives, solar photovoltaics and heat recovery systems on farms
Cost € per t/ CO_2 Eq:	-359
Mitigation Mt CO_2 Eq:	0.029
Cost €M:	-160

This is a series of measures to reduce energy consumption on (principally dairy) farms. These measures include plate coolers to pre-cool milk, variable speed drives (VSD) on vacuum pumps, solar photovoltaics (PV) and heat recovery systems (additional to pre-cooling). All measures either reduce energy consumption or in the case of solar PV, generate energy. Cumulative GHG emissions reductions during the whole lifetime of each measure were 76.3, 25.5, 17.05 and 57.2 t CO_2-e per unit for plate coolers, VSD, heat recovery and solar PV respectively. Uptake was predicted to be 50% (plate coolers), 25% (VSD) and 12.5% (PV and heat recovery). This resulted in a 29.5 kt CO_2-e reduction between 2021 and 2030 assuming linear uptake of measures by 2030. Payback was predicted to be 3 years (plate cooler) and, when used in combination with plate coolers, 15 years for VSD and >20 years for heat recovery and solar PV (Upton et al., 2015).

MEASURE 21: Increased Use of Wood Biomass for Energy Generation

Nature of Measure:	The use of wood thinnings and sawmill residues to displace fossil fuel
Cost € per t/ CO_2 Eq:	-30.7
Mitigation Mt CO_2 Eq:	0.759
Cost €M:	23.4

Wood biomass is assumed to be made up of harvested fuel-wood and sawmill residues for electricity and heat generation and waste wood for heat production. Based on figures by the Programme of Competitive Forest Research for Development (COFORD) and Sustainable Energy Authority of Ireland (SEAI), the resource availability comprises 81 - 267 ktoe (kilotonnes of oil equivalent) from thinnings between 2021-2030, 142 -181 ktoe for sawmill residues and 26- 30 for waste wood. A biomass energy value of 2.5 MWh per tonne is assumed based on a moisture content of 30%. Fuelwood use has increased by 19% from 2011 to 2014 and is projected to increase from 7% of total roundwood production in 2011, to 21% by 2030. This will deliver a mean fossil fuel displacement of 0.7 Mt CO_2-e from 2012- 2030 and a maximum abatement of 0.85 Mt CO_2-e by 2030. Costs were based on €2.5 GJ^{-1} for residues and €6 GJ^{-1} for forestry woodchips (SEAI, 2017a). The cost of forestry plantation is already included in 'forestry measure' costs, so costs are labour costs for thinning with income from harvested wood (priced at an average €13.94 m^{-3}).

MEASURE 22: Increased Use of Short Rotation Coppice & Miscanthus Biomass for Heat Production

Nature of Measure:	Cultivation of willow and Miscanthus for heat production
Cost € per t/ CO_2 Eq:	-20
Mitigation Mt CO_2 Eq:	0.179
Cost €M:	-2.10

Ireland committed to produce 12% of heating demand from renewable sources by 2020 as part of the country's response to the 2009 Renewable Energy Directive (2009/28/EC), biomass being the principle renewable technology for meeting large scale heat demand. It is expected that the introduction of a Renewable Heat Incentive scheme in 2018 will result in an increase in heat generation from biomass. The primary source of biomass for heat generation is expected to come from forestry resources although biomass from energy crops is also expected to make a contribution. However, the extent of the contribution from energy crops is uncertain. The two primary energy crops in Ireland are willow and Miscanthus. Of these two crops, willow can be used in biomass boilers designed for wood combustion whereas the combustion of Miscanthus generally requires more specialised equipment. In this scenario, a combined 15,000 ha of willow and Miscanthus is planted on grassland.

All major inputs and sinks of CO_2, CH_4 and N_2O were considered for emissions associated with Miscanthus and willow replacing low-input beef grassland. As a result there was no net change in soil carbon stocks. It was assumed that energy crop planting is preceded by herbicide application, ploughing and tilling. Coppicing (cut-back) in year 1 and each subsequent harvest with the exception of the last harvest is followed by a herbicide application and by fertilization. The last harvest is succeeded by two herbicide applications to kill the crop and ploughing to remove the crop. For this study, it was assumed that fertilization of willow is necessary to replace crop offtakes and that nitrogen fertilization rates ranged from 50 kg N ha^{-1} yr^{-1} to 130 kg N ha^{-1} yr^{-1} with a mid-point of 90 kg N ha^{-1} yr^{-1}. For Miscanthus, herbicide application was assumed to consist of pre- planting application, one application in each of the first three years and thereafter every two years, two herbicide applications were assumed to be necessary to remove the crop. For this study, we assumed that nitrogen fertilization was necessary to replace Miscanthus crop offtakes and that nitrogen fertilization rates ranged from 50 kg N ha^{-1} to 100 kg N ha^{-1} with a mid-point of 75 kg N ha^{-1}, which was used in this study. Average mature yields of 10 t DM ha^{-1}. Gross GHG abatement from the substitution of fuels for heat (kerosene) was based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2016 inventory report. Net GHG abatement was calculated by subtracting the GHG footprint of willow production from gross GHG abatement. The cost of this measure was calculated using returns for willow production produced by Thorne (2011). The marginal returns were greater than those of the beef enterprise, with cumulative increased earnings of €3.58 million. It should be noted that biomass burning for heat production can have negative interactions with air quality targets, as substantial amounts of particulate matter ($PM_{2.5}$ and PM_{10}) and oxides of nitrogen and sulphur (NO_x and SO_x) can be emitted during combustion, particularly compared to oil or gas.

MEASURE 23: Increased Use of Short Rotation Coppice for Electricity Production

Nature of Measure:	Cultivation of willow for energy production
Cost € per t/ CO_2 Eq:	-10
Mitigation Mt CO_2 Eq:	0.196
Cost €M:	-0.98

Willow chips are currently co-fired with peat in Edenderry power station, Co. Offaly. Gross GHG abatement from the substitution of fuels for electricity was based on fossil fuel replacement and the EFs used by the EPA in their 2016 inventory report. The Short Rotation Coppice Willow (SRCW) production cycle in this model is based on data from Teagasc SRCW Best Practice Guidelines (Caslin et al., 2015) and other LCA studies (Jungbluth et al., 2007). This data describes the inputs required and machinery operations over the lifetime of the willow plantation (22 years). Net GHG abatement was calculated by subtracting the GHG footprint of willow production, which consists of ground preparation and ploughing, fertiliser emissions and harvest emissions (Don et al., 2011; Murphy et al., 2014) from gross GHG abatement. The cost of this measure was calculated using returns for willow production produced by Thorne (2011). Yields of 10 t DM ha^{-1} yr^{-1} were assumed for willow production (9,000 ha). While this would take place on land previously used for beef production, it was assumed that willow production would not affect beef production as beef production would be maintained by increasing stock density as stock densities on beef farms are low. Assuming a mean GHG footprint of 5.4 kg CO_2-e per GJ (Murphy et al., 2014), total gross offsets would be 0.187 Mt CO_2-e by 2030 and yield a margin of €196 ha^{-1}.

MEASURE 24: Biogas Production by Anaerobic Digestion of Slurry and Grass

Nature of Measure:	Digestion of slurry and grass for the production of gas which is used to power combined heat and power (CHP) plants.
Cost € per t/ CO_2 Eq:	115
Mitigation Mt CO_2 Eq:	0.224
Cost €M:	25.8

Anaerobic digestion of biomass produced from Irish grassland (i.e. grass fed-biomass) would produce biogas (55% methane) that could be used directly for heat and electricity generation, or could be upgraded to the same standard as natural gas (bio- methane – 97% methane), injected into the natural gas grid and subsequently used for a range of commercial purposes (Smyth et al., 2011). It should be noted that under the 2050 Carbon-Neutrality as a horizon point for Irish Agriculture Report (Schulte et al., 2013), bioenergy plays a major role in closing the emissions reduction gap. It should also be noted that under this scenario, the primary feedstock for AD would be grass-based, with some contribution from pig slurry and poultry litter. Grass fed AD overcomes the high CO_2 emissions associated with the land-use change associated with the conversion of permanent grassland to crops such as maize. Large scale digestion of cattle slurry alone would not be envisaged as a) it would not contribute substantially to energy generation, b) there are other effective means to reduce slurry methane emissions c) digestate produced as a by- product would have the potential to increase ammonia emissions.

Biogas produced from anaerobic digestion can be used for a range of purposes including electricity and heat generation. When it is upgraded to biomethane (>97% methane content) it may be injected into, and distributed, by the natural gas network. Biomethane has been highlighted by the EU Renewable Energy Directive to be a sustainable transport biofuel.

Wall et al. (2013) in laboratory assessment highlighted that 1 kg of organic matter can produce 308 l of CH_4, using a 1:1 volatile solid ratio (or 1:4 volumetric basis) of grass and slurry. This equates to a potential gross energy production of 235 ha^{-1} yr^{-1}. An economic analysis of a scenario where a large proportion of grass is used in the production of biogas and biomethane has been performed by SEAI (2017b). The 'increased biomethane' scenario generated in this study was assessed as a likely option. Under this scenario, the majority of feedstock for the AD facilities (circa 80%) is derived from grass and slurry fed facilities and biogas production could produce 389 GWh for electricity and 379 GWh for heat production. This results in a mean GHG reduction of 0.224 Mt CO_2-e between 2021-2030, reaching a maximum abatement of 0.361 Mt CO_2-e by 2030. Three-quarters of this reduction arises from fossil fuel displacement by 2030 with the remainder from displaced slurry emissions. Costs include establishment costs of €3.5 million for a 500 kW digester and 450,000 operating costs. Feedstock consists of 15000 tonnes per annum, 2:1 grass:slurry with the price of grass silage set at €28 t^{-1}. Energy price is set at €0.06-0.08 per kWh electricity with a refit tariff of €0.14 per kWh. No gross value added to the wider economy was taken into account and the price of C savings was not taken into account as the objective of the whole study is to generate an optimal C price.

MEASURE 25: Biomethane from Biogas

Nature of Measure:	Digestion of slurry and grass for the production of gas which is processed further to methane which is injected into the natural gas grid
Cost € per t/ CO_2 Eq:	280
Mitigation Mt CO_2 Eq:	0.15
Cost €M:	42

Biogas produced by anaerobic digestion consists of 50% methane and 50% CO_2. Biomethane plants strip out the CO2 to produce almost pure CH_4 that can be injected into the national grid. Under the SEAI (2017) 'increased biomethane' scenario, 1275 GWh equivalent of gas is produced by 50 power plants. The cost of a 6400 kWh plant was estimated at €6.8 million with operating costs of €586,000 and requiring 50,000 tonnes of grass silage per annum. Income is derived from €0.035 kWh yr^{-1} for gas (for polished biomethane only). This will result in a mean cost of €280 per tonne CO_2 abated. It should be noted that the GHG savings displacing natural gas as a source of renewable thermal energy would be less as natural gas produces less GHG per unit of energy than diesel (53 kg CO_2 GJ^{-1} versus 76 kg CO_2 GJ^{-1} in direct combustion). Discount rate is assumed at 4%

over a 15 year payback period

Biofuels:

In the last iteration of the MACC, bioethanol and biodiesel production were included. However, in the interim, the sustainability criteria for biofuels has increased to a minimum 75% total GHG offset across the full life-cycle of biofuel production. This would require further valorisation of products derived from the parent material (e.g. biorefining of plastics, chemicals, soil conditioners.). The costs of this are uncertain. Listed below are two additional measures that may be most likely to contribute to fossil fuel displacement.

MEASURE 26: Oilseed Rape for Biodiesel

Nature of Measure: Cultivation of OSR for energy production

Cost € per t/ CO_2 Eq: 90

Mitigation Mt CO_2 Eq: 0.174

Cost €M: 15.6

The production and use of oil seed rape for use as biodiesel will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions although the cost benefits are highly variable and will depend on grain prices. Oilseed Rape (OSR) emissions were based on an analysis using FarmScoper (Gooday et al., 2014). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major GHGs were considered. It was assumed that OSR would be grown on farms as a break crop. Agronomic operations were assumed to consist of ploughing, tilling, sowing, rolling, spraying, applying fertilizer and harvesting. It was assumed that the OSR area is divided into spring oilseed rape and winter oilseed rape and that spring OSR accounts for 1/3 of the total area. Seed rates, pesticide inputs and the timings of pesticide and fertilizer applications were taken from Hackett et al. (2006). It was assumed that winter crops would receive an autumn herbicide, two sprays of fungicide/insecticide, one spray of boron and a desiccant spray prior to harvest. Nitrogen fertilization used an application rate of 180 kg N ha^{-1} for winter crops and 125 kg N ha^{-1} for spring crops (Wall et al., 2017). A national average OSR yield of 3.6 t ha^{-1} was used in this study. After harvest, it was assumed that the oilseed rape straw was collected and baled for energy use, straw yields were taken from El-Sayed et al. (2003). The calorific value of rape straw was taken from Keppel et al. (2013). It was assumed that the land needed to produce OSR for biodiesel and pure plant oil production would come from the existing tillage base and replace spring barley currently used for animal feed production. The realistic scenario for OSR is based on the production of oilseed for a biodiesel plant with a capacity of 10,000 t annually considering the culinary demand for OSR.

Gross GHG abatement from the substitution of fuels for heat, transport and electricity were based on fossil fuel replacement and the emission factors (Duffy et al., 2018). Net GHG abatement was calculated by subtracting the GHG footprint of imported spring barley feed as well as the difference in cultivation emissions between spring barley and oilseed rape from gross GHG abatement. The benefit of this measure *to the farmer* was calculated using Teagasc costs and returns for oilseed rape compared with spring barley production and calculated at €5.4 million (Phelan et al., 2017). The margin for winter and spring OSR was €371 and €131 ha^{-1} compared to €106 ha^{-1} for spring barley. Associated production costs (minus cultivation) were set at 23 cent l^{-1} and distribution costs at 8 cent l^{-1} (Charles et al., 2013). Diesel price was set at €1.18 with biodiesel's energy density 90.5% of diesel.

MEASURE 27: Sugar Beet for Bioethanol

Nature of Measure:	Cultivation of beet for energy production
Cost € per t/ CO_2 Eq:	200
Mitigation Mt CO_2 Eq:	0.051
Cost €M:	-4.97

The production and use of sugar beet for the production of bioethanol will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Where direct GHG emissions associated with the production of this crop are different from the direct emissions associated with previously grown crops, these differences are accounted for in the calculation of its abatement potential. Annual average fresh yields of sugar beet were provided by the CSO (www.cso.ie). The average beet yield used in this study was 50 t ha^{-1} fresh weight of clean beet, with an assumed 20,300 ha planted by 2030.

Gross GHG abatement from the substitution of fuels for heat, transport and electricity were based on fossil fuel replacement and the IPCC emission factors. Net GHG abatement for the full LCA was calculated by subtracting the GHG footprint of imported spring barley feed as well as the difference in cultivation emissions between spring barley and sugar beet from gross GHG abatement. The cost/benefit to the farmer was assessed in terms of displacing spring barley production. This resulted in a net cost to the farmer of €21 ha^{-1} as margin for barley is €106 and beet was calculated at €85 ha^{-1}. Production and distribution costs were estimated at 27 cent l^{-1} and 8 cent l^{-1} (Deverall et al., 2009; Charles et al., 2013) respectively, with petroleum price set at €1.25 l^{-1} and bioethanol having an energy density 64.8% of petroleum.