MACC 2023:

An Updated Analysis of the Greenhouse Gas Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030

Prepared by Teagasc Climate Centre

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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
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, unless using umbilical systems, 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

FPCM	Fat and Protein-Corrected Milk
FW 2025	FoodWise 2025 (in scenario analyses)
GHG	Greenhouse Gas
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

This third Teagasc Marginal Abatement Cost Curve (MACC) for agricultural greenhouse gas (GHG) emissions from Irish Agriculture was conducted by members of the Teagasc Climate Centre and builds up on the previous reports published in 2012 and 2018 (Schulte et al. 2012, Lanigan et al. 2018). Previous MACC reports 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 2018 Teagasc emphasised that science, technology and policy would all continue to evolve, meaning that a new MACC would be required at a future point. The policy context has also evolved with the setting of sector ceilings for all parts of the Irish economy, including agriculture. Building on the work done in 2012 and 2018, this new MACC now seeks to provide an updated assessment of the GHG mitigation achievable, once again taking 2030 as a horizon point. In particular, advances in **reduced age of finishing**, **animal genetics, feed additives, clover/multispecies swards, fertiliser formulation and manure management** mean that there are a range of new measures for inclusion in this updated Teagasc GHG MACC report. While the previous MACC focused on mitigating agricultural and land-use GHG, this new MACC also includes a suite of land management measures, such as **pasture and cropland soil managemen**t, **forestry sinks** and **management of organic soils**.

1.1. The Policy Context

1.1.1. Climate Action and Low Carbon Development Act

The Act commits Ireland to a legally-binding target of a climate neutral economy no later than 2050, and to a reduction in emissions of 51% by 2030 (compared to 2018 levels). In order to achieve this target, the Climate Change Advisory Council (CCAC) was tasked to develop a programme of economy-wide 5-year Carbon Budgets. The multisectoral budgets developed are as follows:

- 295 $MtCO_2e$ for the period 2021-2025 or (4.8% per annum reduction)
- 200 $MtCO_2e$ for the period 2026-2030 or (8.3% per annum reduction)

The Act required that Sectoral Emissions Ceilings were to be approved by the Government in order to help achieve these targets (Government of Ireland 2022). The major emission sectors (Energy Production, Transport, Industrial, Commercial and Residential Energy Use, Agriculture and Other) were ultimately each assigned sectoral emission budgets for the first two Budget periods (Table 1.1). Agriculture was allocated a sectoral target of reducing emissions by 10% for the first carbon budget (2021-2025) and a further 15% reduction for the second carbon budget (2025-2030). This means that agriculture has a five year budget of 106 $MtCO_2e$ for 2021- 2025 and 96 $MtCO_2e$ for 2026- 2030 with a 2030 target of 17.25 $MtCO_2e$ yr-1 by 2030, equating to a 25% reduction compared to 2018 emissions of 23 $MtCO_2e$.

Table 1. 1: Sectoral ceilings associated with the first two Carbon Budgets (2021-25 and 2026-30) and the 2030 emissions reduction target for each sector.

			Sectoral Ceiling for each 5 year Carbon Budget (Mt CO_2e		
Sector	**Reduction**	**2018 Base year emissions * Mt CO_2e yr^{-1}**	**Carbon budget 1 2021-25**	**Carbon budget 2 2026-30**	**2030 emission limit**
Electricity	75%	10.5 $MtCO_2e$	40	20	3 $MtCO_2e$
Transport	50%	12 $MtCO_2e$	54	37	6 $MtCO_2e$
Buildings (Commercial and Public)	45%	2 $MtCO_2e$	7	5	1 $MtCO_2e$
Buildings (Residential)	40%	7 $MtCO_2e$	29	23	4 $MtCO_2e$
Industry	35%	7 $MtCO_2e$	30	24	4 $MtCO_2e$
Agriculture	25%	23 $MtCO_2e$	106	96	17.25 $MtCO_2e$
Other (Waste, F-gases, etc)	50%	2 $MtCO_2e$	9	8	1 $MtCO_2e$
Unallocated Savings*				-26	-5.25 $MtCO_2e$

* *includes unallocated LULUCF emissions. Significantly, Land-Use, Land-Use Change and Forestry targets were deferred as a) the sector has been undergoing significant changes to its GHG accounting system (from net-net accounting to gross-net accounting, see Section 1.1.4), b) significant changes in emission factors associated with afforested peat soils were being incorporated into the Irish inventory and c) the National Land-Use Strategy report had not been completed.*

1.1.2. FoodVision 2030 and the Sectoral Response to the Climate Act Targets

The goal of FoodVision 2030 is for Ireland to become a world leader in Sustainable Food Systems (SFS) over the next decade. The strategy is built around four Missions:

a) a climate smart, environmentally sustainable agri-food sector
b) viable and resilient primary producers with enhanced well-being
c) food which is safe, nutritious and appealing, trusted and valued at home and abroad
d) an innovative, competitive and resilient agri-food sector, driven by technology and talent

This strategy has the development of a Climate-Neutral Agricultural System by 2050 as a central goal. This was envisaged to occur within the framework of the sectoral budgets provided for under the auspices of the Climate Action and Low Carbon Development (Amendment) Bill. The Strategy proposed to develop plans for the reduction of methane, nitrous oxide and ammonia. In terms of carbon sequestration, the strategy states that any system should align with the proposed EU Carbon Farming Initiative. It is also proposed to scale-up renewable energy (RE) sources, especially anaerobic digestion, solar PV, supply of biomass materials and energy efficiency.

After the publication of the Climate Action and Low Carbon Development Act, the Minister for Agriculture commissioned reports from the Food Vision Dairy Group, and the Food Vision Beef and Sheep Group on measures to mitigate greenhouse gas emissions from the dairy and beef/sheep sectors. A Tillage Food Vision Group has also been established. The Dairy Group Report estimated the potential sectoral mitigation to be 1.4 to 2.1 MtCO_2e by 2030, with fertiliser formulation, feed additives, reduction of N fertiliser use and breeding delivering the bulk of this mitigation. Similarly, the Beef and Sheep Food Vision Group estimated that mitigation from the beef sector would be between 1.5 and 2.2 Mt CO_2e, with the majority of mitigation due to a) reduced age of bovine finishing, b) improved breeding/genetics, c) reduced N fertiliser use and altered fertiliser formulation and d) a reduction in animal numbers due to diversification into activities such as organic farming, afforestation, and biomass production for biomethane.

1.1.3. EU Climate and Energy Legislation

The overall EU effort in the period to 2030 has been 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% reduction 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. The Effort Sharing Regulation (ESR) set Ireland a national target of 30% by 2030, to be achieved by linear reduction from 2021-2030 based relative to a 2005 baseline. In addition, Ireland was 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). However the proposals to alter EU LULUCF regulations has reduced the efficacy of this flexibility as the accounting mechanism is proposed to change to gross-net reporting from 2026 onwards, and using this accounting, Irelands LULUCF sector is an emissions source rather than a sink.

The EU has also developed the *Farm to Fork Strategy* which aims to make food systems fair, healthy and environmentally-friendly. It aims to develop sustainable food production and processing systems, develop sustainable consumption and to reduce food waste. As part of the Strategy, a Carbon Farming Initiative is also being developed as a voluntary carbon offsets scheme. This would allow land managers to earn carbon credits by changing land use or management practices to store carbon or reduce greenhouse gas emissions.

1.1.4. Proposals for regulation amending EU LULUCF Regulation (EU) 2018/841

The 2021 proposed amendment to the EU LULUCF regulation ((EU) 2018/841) signals a fundamental shift in accounting principles from a "no debit rule" net-net system and forest reference level to a gross net system with a shared LULUCF target for the whole EU. This proposal is part of the Fit for 55 legislative package to increase the carbon removals and to achieve climate neutrality in the combined agriculture, forestry and other land-use (AFOLU) sector by 2035 at EU level. One of the principal reasons for this proposed change is to simplify reporting across agriculture and land-use in order to combine the agriculture non-CO_2 greenhouse gas emissions with the land use, land use change and forestry sector, thereby creating a newly regulated AFOLU sector. These rules will be implemented from 2026 onwards, with the (already assessed) period 2021-2025 continuing to be reported under the current rules.

The proposals change both the accounting rules and Member State (MS) obligations in terms of achieving net LULUCF removals from those set out in the current LULUCF regulation in the following ways.

- Compliance with allocated national targets will be verified on the basis of reported greenhouse gas emissions and removals.
- For the period 2026-2030, binding annual targets of net greenhouse gas removals will be set for each Member State and will result in a target of 310 million tonnes CO_2 equivalent for the European Union as a whole. Furthermore, the European Commission proposes to combine the agriculture non-CO_2 greenhouse gas emissions with the land use, land use change and forestry sector, thereby creating a new AFOLU sector.
- The Commission's proposals ultimately set a target for an EU-wide Net-Zero AFOLU sector by 2035.

The Proposals envisage setting a LULUCF target for each Member State analogous to the Effort Sharing Regulation (ESR) targets no later than 31 December 2025. The proposed regulation sets the ambition for net-zero emissions from AFOLU by 2035 and negative AFOLU emissions thereafter.

There is a large variation in LULUCF net removals and emissions among Member States (Figure 1.2). However, the majority of Member States will either benefit marginally or not lose out to any great degree from the changes proposed by the European Commission. Ireland is disadvantaged for three reasons:

1. Ireland has a large proportion of its current forest stock on histic (peat) soils, with the majority of this planted prior to 1990.

2. Ireland has a large proportion of peatland under agricultural management. Again, the vast majority of drainage of this land was prior to 1990. It is also unclear as to the current effectiveness of the existing drainage and the CO_2 emissions associated with those soils.
3. A stated above, Ireland was granted flexibilities in the ESR for land-use to 'offset' some of its emissions – the move to gross-net reporting effectively eliminates this flexibility.

1.2. Ireland's Agricultural Greenhouse Gas and Land-Use Emissions Profile

Agricultural GHG emissions comprise 38% of national greenhouse gas emissions and in proportional terms have remained relatively static since 1990, when agriculture comprised 37% of total emissions. However, the absolute quantum of emissions has increased by 15.4% from 20,479 ktCO_2e in 1990 to 23,626 ktCO_2e in 2021 (Figure 1.1). Between 1990 and 1998, the sectoral emissions increased by 13.7%, reflecting an increase in bovine and ovine numbers and increased synthetic nitrogen use. Post-1998, Common Agriculture Policy (CAP) reform which removed commodity price supports and introduced direct payments to farmers instead, led to emissions from the sector decreasing by 15.7% to 19,598.3 ktCO_2e in 2011. This decrease reflected large reductions in the sheep population and synthetic nitrogen fertiliser use, plus a smaller decline in suckler cow numbers. Importantly, emissions in 2021 were marginally higher (0.9%) compared to the 2018 benchmark and this reinforces the scale of the challenge for the sector to achieve the emissions ceilings target by 2030.

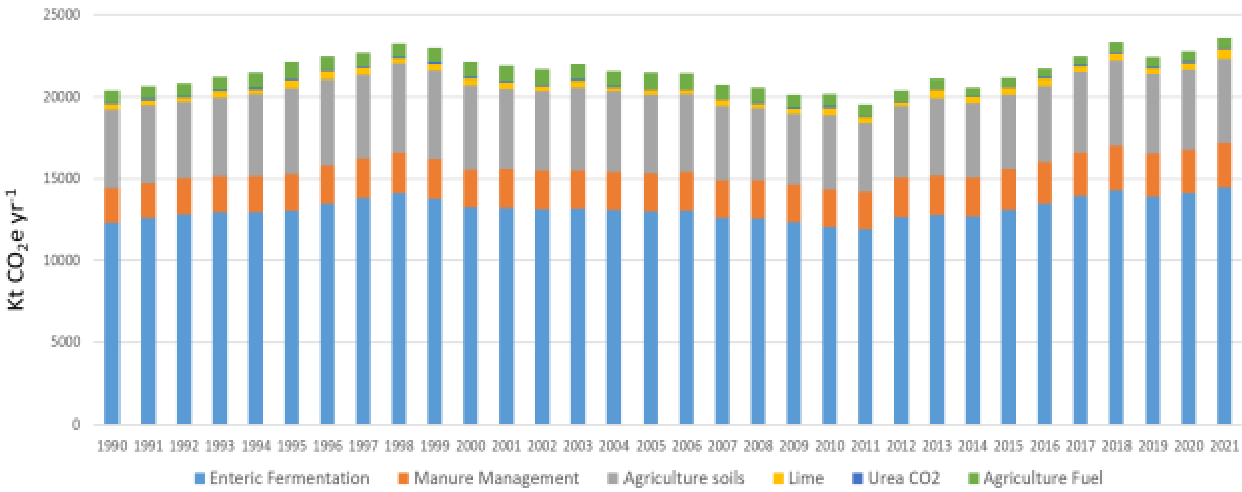


Figure 1.1: Greenhouse gas emissions profile for agriculture (1990-2021)

Source: EPA National Inventory Report 2022

Agricultural emissions are dominated by methane (CH_4), which comprises 70% of Ireland's agricultural emissions. The principal source of methane (80%) is bovine and ovine enteric fermentation of carbohydrate in the rumen with the remainder attributable to the management of bovine, porcine and poultry manures, particularly liquid manure (slurry) systems. Nitrous oxide (N_2O) from fertiliser, manure and animal excreta deposited directly onto pasture constitutes the vast bulk of the remaining emissions (25%), with minor CO_2 emission sources associated with liming and urea application to land and fuel combustion (5%).

The Land-Use, Land-Use Change and Forestry (LULUCF) sector in Ireland is atypical compared to most EU countries, in that it is a net GHG emitter, whereas LULUCF is a net sink for most other European countries (i.e. GHG removals are greater than emissions, see Figure 1.2). This is mainly due to two factors: 1) the large proportion of peat soils, which results in large emissions, from agriculturally-managed (drained) peat soils, peat extraction for energy and horticultural use and from afforested peat soils and 2) The low proportion of forest cover (11.6%) in Ireland compared to other countries. Total LULUCF emissions have increased 22% between 1990 and 2021 (from 6009 ktCO_2e to 7338 ktCO2e) and more significantly by 14.6% since 2018 (Figure 1.3). The historical increase from 1990 to 2016 was primarily due to increased peat extraction for power generation, which has now largely ceased. Subsequent increases have been driven primarily by a decreasing forest sink, which is due to the combined impact of low planting rates over the last decade and the age profile of Irish coniferous plantations, which are due for harvesting over the next decade (Duffy et al. 2022, DAFM 2022).

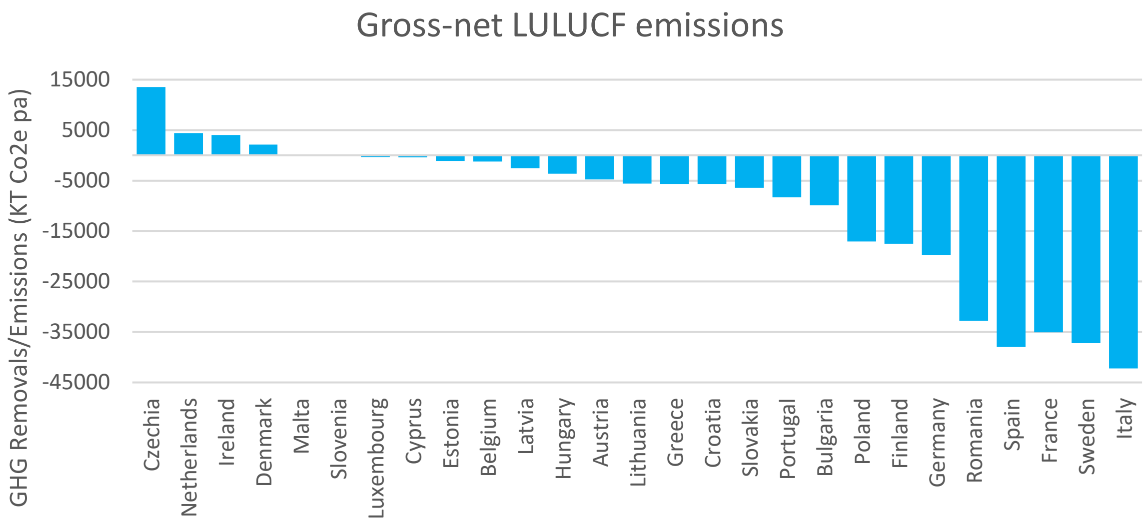


Figure 1.2: Gross-Net LULUCF emissions/removals from all Member States in 2019. Source IPCC.

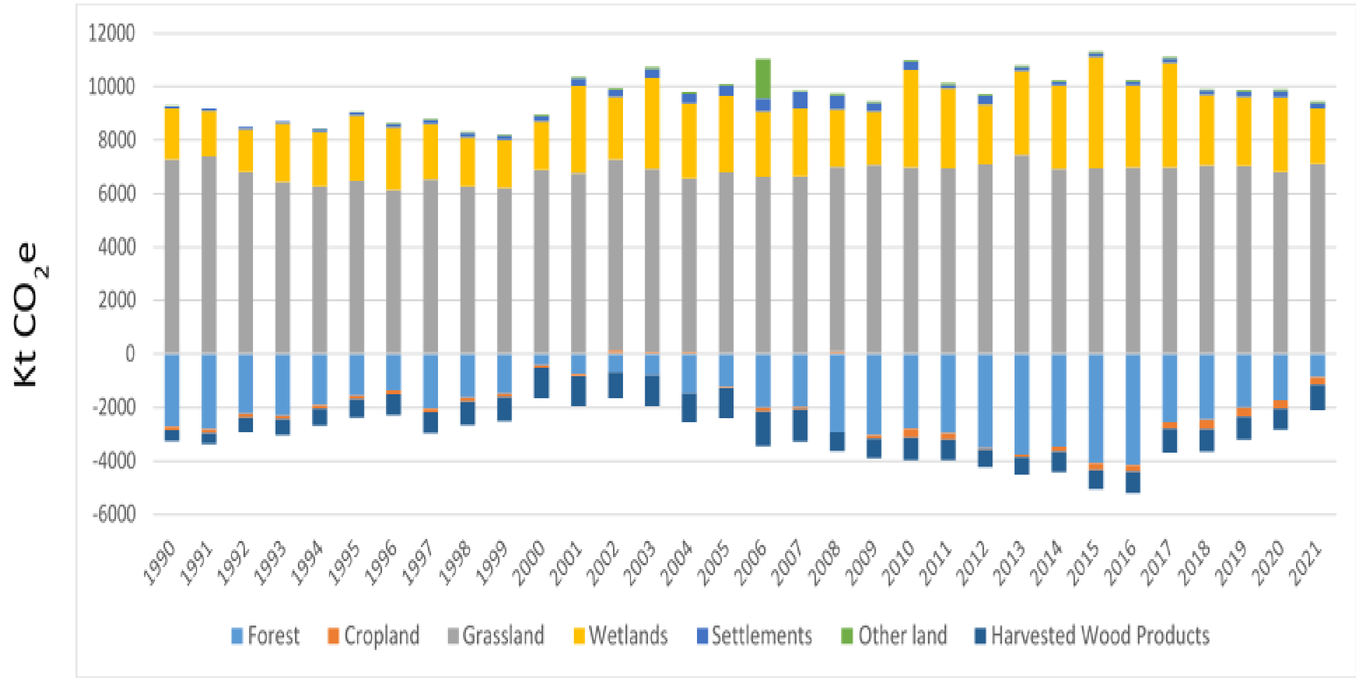


Figure 1.3: Greenhouse gas emissions profile for land-use, land-use change and forestry (1990-2021). Source: EPA National Inventory Report 2022

1.3. Mitigation: The adoption of technologies

For the last 15 years, researchers in the newly established Teagasc Climate Centre have been developing technologies to address future agricultural GHG emissions. For the purposes of development of a MACC, three key questions emerge:

1. Which technologies should farmers use?
2. Which farmers are likely to adopt each technology?
3. When will farmers adopt the technology and at what rate will the technology be implemented until it becomes mainstream?

1.3.1. Available Technologies

Efficiency Measures: One way to mitigate GHG emissions is to produce food more efficiently i.e. with fewer inputs. Efficiency measures reduce emissions to the atmosphere for a given volume of agricultural output. Established technologies that can reduce emissions through efficiencies include:

- higher genetic merit and animal productivity (e.g. higher yields, better animal health, higher fertility, higher grass growth),
- changes to production techniques (e.g.) extending the grazing season length for ruminant animal systems
- improved soil nutrient management (more selective application and efficient utilisation of synthetic fertilisers)
- use of sexed semen to increase the quality of dairy-sourced animals for beef production systems and reduce age at finishing.

These technologies change the relationship between the rate of emissions and the rate of production, but in the context of a sector where the volume of output is growing, such measures will only dampen emissions increases rather than reduce the absolute quantum of emissions.

Absolute emissions reduction: In the previous MACC analysis, reductions in absolute sectoral GHG emissions focussed on technologies that reduced N fertiliser use or switching to low emission N fertilisers. These included

- Achievement of good soil nutrient and pH status
- Optimal use of animal manures, digestates and the development of bio-based fertilisers
- The development of low-emission mineral nitrogen fertilisers.
- Reducing N excretion by optimising crude protein content in livestock diets

In addition, reducing N fertiliser will also contribute to achieving improved water quality and fulfilling obligations under the Nitrates Directive.

Since 2018, technologies for reducing methane emissions have emerged and these are focused around a) feed additives, such as 3-NOP, halides or fatty acid supplementation, b) the use chemical amendments or aeration to reduce manure methane, and c) reducing the age of finishing of livestock (thus reducing lifetime methane/N_2O from these animals). In the future, breeding for low methane animals may hold promise, and indeed higher Economic Breeding Index (EBI) dairy cows have been shown to have lower than expected enteric methane emissions (Lahart et al. 2021, 2022).

1.3.2. Adoption of measures

Realising the GHG mitigation potential of agriculture is ultimately dependent on farm-level decisions based on how the adoption of a measure or suite of measures 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. Technological mitigation options that incur a cost must, therefore be incentivised either via grant-aid, market price return, or the generation of a carbon market that places a financial value on 'carbon'.

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 if policy is to be effective and encourage adoption of GHG mitigation practices (OECD, 2012).

In order to promote adoption of the measures previously identified within the Teagasc 2018 MACC, Teagasc have developed the Signpost Farm Programme, including a comprehensive network of best-practice demonstration farms as well as a dedicated advisory programme to provide wider dissemination and support to reach individual farmers. This is a multi-annual campaign to lead and support climate action across all Irish farmers. The programme's aim is to achieve early progress in reducing gaseous emissions from Irish agriculture whilst simultaneously improving water quality and biodiversity and reducing costs to farmers. It will also act as a test bed for on-farm carbon sequestration measurements so that, in time, national-level land-use and land management sequestration factors can be incorporated into the national Greenhouse Gas inventory. It is a collaborative programme, led by Teagasc, in collaboration with over 60 partner and supporter organisations across the agri-food sector.

1.3.3. The Diversification of Irish Agriculture

Irish agriculture is dominated by dairy and livestock production, with the result that GHG emissions are dominated by livestock-related methane and N_2O emissions. Diversification of farming activities may offer livestock farmers alternative income streams, whilst also reducing emissions that result from partial de-stocking. This diversification may come from

- Shift to organic production systems
- Producing feedstocks for bioenergy production
- Expansion of the national tillage area
- Increased afforestation

Organic farming covered around 14.7 million hectares of agricultural land in the EU in 2020 corresponding to 9.1 % of the total utilised agricultural area (UAA). This represents a 54% increase in the area under organic production compared to levels in 2009. Ireland, by contrast, has less than 2% of UAA under organic production. However, an Irish Government target of 7.5% UAA has been set for 2027 and there has been a large increase in applicants to the new Organic Farming Scheme, which will increased the proportion of UAA under organic production to 4.5% (DAFM 2022), with further uptake expected to continue in the years ahead. The more widespread adoption of organic systems would result in an increased uptake of legumes, reduced N usage and also reduced stocking density in some cases.

The production of biomass feedstocks for use in the energy sector has been identified as a key diversification opportunity as Ireland needs to be on a trajectory to increase the overall renewable energy share from the current 12.5% to 34.1% by 2030, as set out in the National Energy and Climate Plan (NECP). Whilst much of this target will be met by wind and solar energy production, a substantial proportion will be met by the increased mobilisation of wood residues and biomethane.

The Government has also released the Circular Economy Strategy, which aims to keep materials, components, and products in use in the economy for as long as possible. Ireland has a circulatory rate of just 1.6%, lagging far behind the EU average of 11.9%. The Circular Economy Strategy and associated National Food Waste Prevention Roadmap 2023-2025 aims to reduce food waste by 50% by 2030

1.4. The GHG efficiency of Irish Agriculture

Recent estimates put the global GHG emissions from the agriculture and land-use sectors at between 21-33% of global GHG emissions (IPCC 2022, Tubiello et al. 2021), with 75% arising from non-Annex 1 countries, principally South and East Asia and Latin America (Lamb et al. 2021). FAO projections suggest that increases in global population and wealth will increase demand for dairy and meat by more than 50% by 2050 (van Dijk et al. 2021). Projections also indicate that the increase in demand for both meat and dairy products will slow after 2030. 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, Lamb et al. (2021) analysed global GHG emission trends over the last 20 years and found that agricultural encroachment into tropical forest areas has driven recent increases in AFOLU emissions in Latin America, South-East Asia and Africa. 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.

Previous studies comparing the carbon (C) footprint of a range of agricultural products across the EU-28 member states from the Joint Research Centre of the European Commission 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 was supported by the FAO, which estimated that the carbon footprint of milk was lowest in 'temperate grass-based systems', such as those that are commonplace in Ireland (FAO, 2010). More recent studies have continued to show that Irish dairy systems are efficient compared to other countries, with the emissions intensity for milk ranging from 0.75 kg CO_2e kg^{-1} FPCM to 1.07 kg kg^{-1}FPCM and beef ranging from 17.5 to 28 kg CO_2e kg^{-1} carcass weight (O'Brien et al. 2015, Rice et al. 2017, Lorenz et al. 2019, O'Brien et al. 2020, Gaillach & Marbach 2021, Mazzetto et al. 2021 Samsonstuen et al. 2021, Buckley & Donnellan 2020).

This positive performance has been driven by on-going gains in resource use efficiency by Irish agriculture since 1990. Teagasc research shows that the carbon 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, Kelly et al. 2020). Similarly, the 'Nitrogen-footprint' of Irish produce has reduced by c. 25% since 1990. 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 the national farm surveys have shown that the most profitable dairy and beef farms tended to also have the lowest carbon and nitrogen footprints (O' Brien et al., 2015, Buckley et al. 2019, Buckley & Donnellan 2020, 2022). However, these farms also tend to have the highest 'per hectare' emissions.

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 in bovine or ovine populations in order to aid meeting emissions 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 agriculture 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 (1) flexible implementation of mitigation obligations was required at national and global level and (2) the need for a wider consideration of technological mitigation options. The results also indicate that a globally effective reduction in agricultural emissions requires (3) multilateral commitments for agriculture to limit emission leakage and may have to (4) 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_2e kg^{-1} beef and compared favourably to Brazilian emissions, which were in excess of 30 kg CO_2e 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. 2011). Recent studies have quantified a range of 8.5 kg CO_2e kg^{-1} beef (dairy calf to beef) to 12.5 kg CO_2e kg^{-1} beef (suckler beef), with a large degree of variation depending on the model used (O'Brien et al. 2020).

1.5. The Challenge of Mitigation

In 2022 Teagasc launched the Teagasc Climate Action Strategy focusing on actions achieve both Climate and Biodiversity targets for Irish Agriculture. The strategy sets out a road map on how these targets can be achieved without impacting on the competitiveness of the agri-food sector. To achieve this, Teagasc has significantly increased its resources devoted to climate and biodiversity related research and knowledge transfer. There are three key platforms in the new Climate Action Strategy:

- A Signpost Advisory Programme
- A Sustainability Digital Platform (AgNav)
- A Virtual Climate Research Centre

The new virtual Climate Research Centre will co-ordinate climate and biodiversity research and innovation to accelerate efforts to bring "almost ready" and "early stage" technologies to deployment stage. The Centre will facilitate the Irish agriculture sector to meet its commitments in reducing greenhouse gas emissions and improving biodiversity. The Centre has employed over 20 new research staff to significantly increase Teagasc resources to tackle the Climate and Biodiversity Crisis. This National Centre builds upon the existing research infrastructure and human capital, working with national and international organisations and institutions to create effective, trusted partnerships. The Centre will provide independent robust scientific and technological solutions to lead the agri-food sector towards climate-neutrality by 2050. The Centre will strive to be a world class agri-food climate science centre that will enhance Ireland's reputation as a global leader in this area. It will also address Ireland's wider environmental objectives to improve biodiversity, water quality and reduce ammonia emissions, whilst at the same time seeking to enhance the economic and social pillars of sustainability.

Across the six Centre pillars of Methane, Nitrogen, Carbon, Biodiversity, Diversification, and Adaptation, research will focus on existing and new measures to reduce emissions and address the challenge of achieving a climate neutral agriculture forestry and other land-use sector. The pillars will be supported by 3 cross cutting themes food systems, supporting policy and signpost farm programme to directly support farmers, policy makers and the wider food industry. Research from the Climate Centre will be used to further develop the AgNav digital sustainability tool to provide farmers with an estimate of their impact on greenhouse gas emissions and biodiversity. Existing and new measures will then enable the Signpost Advisory Programme to work with farmers to develop a farm specific action plan to reduce emissions and enhance biodiversity, without impacting negatively on farm profitability.

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 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 have also participated in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land-Use and, in particular, were authors on the chapter relating to Food Security and Climate Change and have engaged in the UN expert panel for Mitigating Agricultural Nitrogen.

2. Marginal Abatement Cost Curves (MACC)

2.1. The 2012 and 2018 MACC Analysis

A marginal abatement cost curve (MACC) is a graphical representation of the cost of reducing a unit of greenhouse gas emissions by one monetary unit, as the level of emission reduction increases. The MAC curve is typically upward sloping, meaning that as the level of pollution reduction increases, the cost of reducing each additional unit of GHG emission also increases. The MAC curve is used to evaluate the cost-effectiveness of different GHG reduction options, as well as to understand the trade-off between the cost of reducing emissions and the benefits associated with this emissions reduction. For example, the MAC curve can be used to identify the most cost-effective way to reduce emissions, given a target level of emissions reduction, or to determine the level of emissions reduction that can be achieved at a given cost. The shape of the MAC curve is influenced by factors such as the availability of technology, the level of investment in research and development, and the structure of the economy. For example, if there are low-cost technologies available to reduce pollution, the MAC curve will be relatively flat, meaning that the cost of reducing pollution will be low. Conversely, if there are few available technologies to reduce pollution, the MAC curve will be steeper, meaning that the cost of reducing pollution will be higher.

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 et al. 2012). It was largely based on experimental research 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.

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_2e in 2010 to 20.0 Mt CO2-e by 2020, a relative increase of 1.2 Mt CO_2-e, or c. 7% (Donnellan and 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.

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 per annum. Of this total, c. 1.1 Mt CO_2-e of this 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}.

The 2018 MACC analysis identified 27 measures that would contribute to GHG reduction. These were split into three separate MACC's: the agriculture MACC consisting of 14 measures, a LULUCF

MACC consisting of five measures and a bioenergy MACC consisting of a further eight measures. The *annual mean* abatement potential arising from cost-beneficial, cost-neutral and cost-positive mitigation measures for *agricultural* emissions (methane and nitrous oxide) and assuming linear rates of uptake (farmer adoption of a measure) was 1.85 Mt of carbon dioxide equivalents per year (CO_2-e yr^{-1}) between 2021 and 2030, compared to the S1 with no mitigation. In terms of Land Use mitigation, the enhancement of CO_2 removals was forecast to potentially remove another 2.97 Mt CO_2-e yr^{-1} over the period 2021-2030. 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 yr^{-1} per annum from 2021-2030, mainly associated with the displacement of fossil fuel usage. By 2030, assuming the maximum level of uptake, total mitigation was calculated 8.99 MtCO_2-e yr^{-1}, comprising of 3.07 Mt CO_2-e yr^{-1} from agriculture, with further mitigation of 3.89 Mt CO_2-e yr^{-1} and 2.03 Mt CO_2-e yr^{-1} from the land-use and energy sectors respectively. The costs of these measures were observed to be highly variable, ranging from -€45M to +€58M, with variation due to uptake rate, method of adoption and timing of uptake.

Textbox 2. 1: What is a Marginal Abatement Cost Curve?

A marginal abatement cost curve (MAC curve) is a graphical representation of the cost of reducing emissions of greenhouse gases (GHGs) or other pollutants by a given amount. The curve shows the marginal cost of abatement, which is the cost of reducing one additional unit of emissions. Figure 2.1 below provides a simplified, hypothetical example of a MACC.

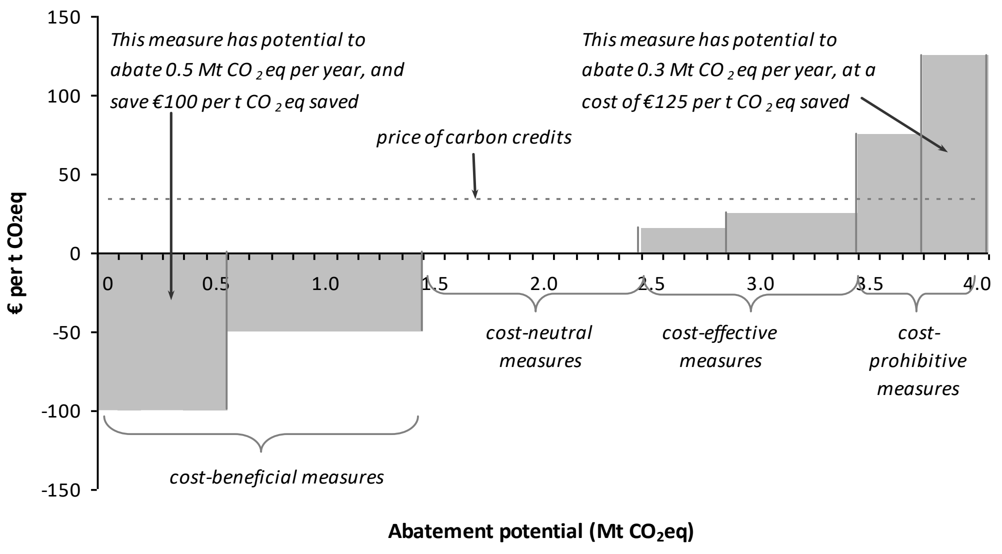
A MACC provides two elements of information:

1. It ranks the mitigation measures from cost-beneficial measures (i.e., measures that not only reduce GHG emissions, but also save money) to cost-prohibitive measures (i.e., measures that save GHG emissions, but are expensive). Cost-beneficial measures have a "negative cost", and are those in Figure 2.1 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.

The MAC curve typically shows the quantity of emissions that can be reduced on the horizontal axis (the units on the figure need to be Mt CO2e yr-1) to keep it consistence with the text) and the cost of achieving that reduction on the vertical axis. The curve is upward sloping, reflecting the fact that as more emissions are reduced, the marginal cost of further reductions increases.

In addition, a MACC commonly includes an indication of the price of carbon credits. "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.



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

2.2. Objectives and Approach in the Current Study

The objective of the current analysis was to assess the total abatement potential and associated marginal costs/benefits associated with agricultural, LULUCF and Bioenergy GHG mitigation measures. These abatement potentials and costs are subsequently presented as a marginal abatement cost curves (MACC). The ultimate aim was to quantify whether the adoption of technical mitigation measures could achieve the sectoral targets set under the Climate Action and Low Carbon Development (Amendment) Act (2021).

2.2.1. Agricultural and fossil fuel emissions

The impact of a range of mitigation measures (see below) were assessed for their potential to reduce agricultural GHG emissions, LULUCF emissions, or GHG emissions from energy generation, by incorporating them into a 'top-down' flow inventory approach based on the IPCC Good Practice Guidelines (IPCC 2006, 2014, 2019) and using identical approaches to those used for the calculation of the EPA's national GHG inventory for agriculture. The advantage of this approach was that the additive impacts of measures on Agriculture, Forestry and Other Land-Use (AFOLU) emissions could be assessed collectively. This meant that interactions between measures on various GHG emission sources could be taken into account. 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 also the impact of improved number of grazing days on methane could also be quantified. Similarly, the positive impact of slurry aeration on manure methane emissions was quantified, but also the measure's negative impact on ammonia emissions. In many cases, the order in which measures were employed was important. This is especially true for N_2O abatement, as any measure which impacts the total amount of N available will have downstream impacts in terms of the N cascade, as the various stages of agricultural N flow are interdependent. Therefore, nitrogen abatement measures are interdependent and should be applied in a logical sequence to minimize overall emissions in the system. Importantly, combinations of measures *are not simply additive in terms of their combined emissions reduction capacity*. Applying abatement techniques upstream may lead to increased emissions downstream, as more nitrogen is retained in the system, e.g. slurry additives reduce ammonia losses during storage leading to preservation of nitrogen, if the material is then landspread, N_2O emissions can increase based on the increased nitrogen content of the slurry spread. Conversely, if N is conserved throughout the entire nitrogen management chain and even prior to that, through reduced crude protein intake in animal diets, this will ultimately lower N emissions throughout the system and by improving nutrient use efficiency of organic manures, will lead to reduced need for synthetic fertiliser. Reduced application of chemical N will then in turn lower emissions associated with synthetic fertiliser use.

Other measures interact between different GHG's. For example, the impact of increasing the proportion of protected urea fertiliser used relative to calcium ammonium nitrate (CAN) decreases GHG emissions through reduced N_2O emissions, but it also increases additional CO_2 emissions from fertilisers. 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 emissions, while aeration reduces methane by 40% but increases ammonia by 15%- 20%. 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 (Ogunpaimo et al. 2022)

2.2.2. Carbon sequestration and emissions

2.2.2.1. Grassland and cropland

In order to simulate the impact of land management on soil organic carbon (SOC), the DNDC and DAYCENT models were used. DNDC was developed originally to simulate soil C and N cycling (Li et al., 1992) and gained popularity due to its detailed biochemical equations describing decomposition, nitrification and denitrification processes. It was later expanded to simulate water and N movement (Li, 2007) and full farm nutrient cycling (Li et al., 2012) and now contains sub-models for simulating crop biomass, decomposition, nitrification denitrification, fermentation and ammonia volatilization. The model simulates a very wide array of agricultural management and crop types. The input requirements are reasonable and it can be applied with relative ease. As a result, DNDC has been used extensively worldwide (Ehrhardt et al., 2018, Brilli et al., 2017, Zhang and Niu, 2016, Gilhespy et al., 2014, Giltrap et al., 2010). This model has an advantage in that it has been developed to simulate a wide range of eco-systems including croplands, grasslands and wetlands and has been extensively used for peat soils as well as mineral soils (Deng et al. 2015).

The version used in this analysis is DNDC v.CAN (Smith et al. 2020). This version has been specifically developed to more accurately simulate the impact of impeded drainage as well as simulating the impact of drainage installation on soil C and N dynamics. Ireland-specific empirical growth curves for grass and crops, dynamic biomass fractioning, dynamic plant C:N ratios as well as other crop growth specific climate factors have been incorporated into this model and have been validated for Irish agricultural systems (Li et al. 2011, Abdalla et al. 2013, O'Sullivan et al. 2015, Khalil et al. 2016, Paul et al. 2018, Zimmerman et al 2018).

The DAYCENT (Daily Century) model is also an ecosystem-level biogeochemical model used to simulate the cycling of carbon, nitrogen, and other elements over time (Parton et al. 1998, DelGrosso et al. 2009). It is primarily used to study the impacts of land use and management practices, such as crop rotations, tillage practices, and fertilizer applications, on ecosystem processes and greenhouse gas emissions. The DAYCENT model is based on the Century model, which simulates long-term ecosystem carbon dynamics over periods of centuries. However, the DAYCENT model operates at a daily time scale and simulates the cycling of carbon and nitrogen through the soil-plant-atmosphere system, as well as the effects of soil moisture, temperature, and other environmental factors on these processes. It can be used to predict the impacts of various land management practices on ecosystem services such as carbon sequestration, soil health, and crop production. Similar to DNDC, the DAYCENT model has been used in a wide range of applications, including in agroecosystems, grasslands, forests, and wetlands, but is unable to satisfactorily simulate processes on highly organic (histic) soils.

2.2.2.2. Forestry

The Carbon Budget Model, developed by the Canadian Forest Service (CBM-CFS), was used for modelling greenhouse gas (GHG) profiles of the national estate (Kurz et al. 2009). The modelling was conducted by Fers Ltd who complete this for the EPA and DAFM for inclusion in the national inventory. CBM-CFS is a carbon modelling framework for stand and landscape level forest ecosystems. It has been under development by the Canadian Forest Service for over 20 years and is compliant with the requirements under the International Panel for Climate Change Good Practice Guidance for Land Use, Land-Use Change and Forestry. There are numerous examples of its use globally (Kurz et al., 2009), including in Canada, at European scale by the European Commissions' Joint Research Centre (Pilli et al, 2018) the Czech republic, Poland and in Ireland (EPA, 2022, Black et al., 2022).

A full description of the calibration and validation of the CBM_CFS model for Irish forestry is presented in the Irish Greenhouse gas inventory report (EPA, 2022), the Irish national forest accounting plan (NFAP, 2020) and recent modelling work done for the Coillte estate (Black et al., 2022). More details are given in Section 4.

2.2.3. 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 the 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 anaerobic digestion where, due to the nature of the investment required, the net profitability will be achieved beyond the 2030 commitment period.

Cost Scenarios: Due to the high level of uncertainty with respect to the costs of the measures, two cost scenarios were simulated. The lower cost scenario priced fuel at €0.53 l^{-1}, N fertiliser at €1.20 $kg^{-1}N$, P fertiliser at €2.62 $kg^{-1}P$ and lime at €25 per tonne. The higher cost scenario priced fuel at €1.30 l^{-1}, N fertiliser at €2.60 $kg^{-1}N$, P fertiliser at €3.84 $kg^{-1}P$ and lime at €35 per tonne. Other costs specific to individual measures are presented in detail for each measure in Section 4.

2.2.4. Uncertainty & Sensitivity Analysis

Sensitivity of the abatement potential was assessed for individual measures (in terms of uptake rate, price of inputs and cost savings, % reductions, and area applicable, etc.) and with respect to factors impacting on the whole sector (future activity data, such as animal numbers, fertiliser use, etc.). The details of the individual measure uncertainty analysis is presented in detail for each measure in Section 4.

2.2.5. 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 presented in this report, individual measures were selected and included on the basis of the following criteria: Measures must be applicable to farming systems common in Ireland; 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. 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 efficiency measures** included were:

1. Dairy Economic Breeding Index (EBI)
2. Improved beef genetics (Replacement and Terminal Indexes)
3. Animal health
4. Extension of grazing season

The absolute **agricultural mitigation measures** were as follows:

5. Reduced age of finishing (bovine)
6. Liming
7. P impact on N_2O emission factor

8. Clover and multi-species swards
9. Reduced crude protein (in bovine and porcine diets)
10. Fertiliser formulation (protected urea and low nitrate compounds)
11. Addition of lipids/fatty acids to bovine diets
12. Bovine feed additives
13. Low Emission Slurry Spreading (LESS – trailing shoe and trailing hose uptake)
14. Slurry amendments and acidification
15. Slurry aeration
16. Drainage of mineral soils
17. Use of Digestate
18. Impacts of Diversification on Livestock numbers

In addition, two of the efficiency measures (extended grazing and dairy EBI) have a component portion of their mitigation that results in absolute GHG reductions. In the case of extended grazing, the methane yield (Y_m) of animals grazing fresh grass is lower than that for animals fed grass silage or hay. In the case of dairy EBI, higher EBI cows have a lower than expected Y_m compared to lower EBI cows.

Land-use mitigation strategies to enhance carbon (C) sinks or reduce C loss from the Land-Use, Land-Use Change and Forestry (LULUCF) sector included strategies to increase forestry and hedgerow biomass stock as well as enhancing C sequestration in soils. Forestry was subdivided into individual sets of measures and a MACC for forestry was generated in conjunction with Kevin Black (FERS Ltd.) and John Redmond (DAFM). The forestry MACC measures are as follows:

19. Afforestation
20. Reduced deforestation
21. Extending forest rotations
22. Replanting of former afforested peats with birch
23. Agroforestry
24. Hedgerows (new and hedgerow management)

The measures to enhance soil organic carbon (SOC) levels in agricultural soils and reduce CO2 emissions associated with C mineralisation of agricultural peat soils were as follows:

25. Grassland management (optimising pH, fertilisation, etc.)
26. Water table manipulation in peat soils
27. Cover crops
28. Straw incorporation
29. Addition of manure to cropland

Energy measures were included that displaced fossil fuel emissions with bio-based energy or decreased energy use on farms.

30. Biomethane

31. Wood energy
32. Biomass crops (heat and electricity)
33. Energy efficiency

A detailed description of each individual measure is given in Section 7.

2.2.6. Levels of Uptake and Pathway Definition

In the previous MACCs, only one level of uptake was examined and only a linear uptake of measures was assumed. However, as there is now a sectoral target to be achieved, this analysis investigated two different levels of uptake of measures:

Pathway 1 which had uptake levels similar to the 2018 MACC and/or Dairy/Beef Food Vision and

Pathway 2 which in many cases doubled the uptake ambition level or brought it close to the biophysical potential of a measure.

The uptake levels and assumed shape of the uptake curve are shown in Table 2.1. Well-established mitigation measures, such as fertiliser formulation, clover and lime application, had a linear rate of uptake applied. Similarly, for breeding measures, such as EBI and beef genetics, a linear rate of response was assumed due to the gradual nature of uptake of these breeding measures. In the case of new measures, such as feed additives, a sigmoidal rate of uptake was modelled. Conversely, the uptake of Low Emission Slurry Spreading (LESS) has a front-loaded, convex curve-linear response fitted for the rate of uptake as all Nitrates derogation farmers have to apply slurry by LESS (Table 2.1).

*Table 2.1**:** Uptake levels and response curve rate shape for individual MACC measures*

Sector	**Measure**	**Uptake rate response curve**	**Current (2018) situation**	**2030 - Pathway 1**	**2030 - Pathway 2**
Agriculture	Dairy EBI	Linear	€190 per cow	€240 per cow	€240 per cow
	Reduced Age of Finishing	Linear	25.2 months	2 months earlier	3 months earlier with sexed semen
	Extended Grazing	Linear	227 days	80 days extra grazing for 10% of bovine population	80 days extra grazing for 10% of bovine population
	Liming	Linear	1.04M tonnes	2 M tonnes	2.5 M tonnes
	Clover & MSS	Linear	16.98 kha	472 kha	757 kha
	Phosphorus Impact on N_2O emissions	Linear		15% move to Index 3	30% move to Index 3

Sector	Measure	Uptake rate response curve	Current (2018) situation	2030 - Pathway 1	2030 - Pathway 2
	Reduced Crude Protein	Linear	0% (current CP = 18%)	2% CP reduction 40% Bovines, 3% reduction 40% Pigs	2% CP reduction 90% Bovines, 3% reduction 80% Pigs
	Protected Urea	Linear	24% urea 3.5% CAN	65% CAN replaced with PU 100% Urea to PU	75% CAN replaced with PU 100% Urea to PU
	Protected Urea + Nitrification Inhibitor	Linear	0	0	20% CAN replaced by PU + NI
	Low Nitrate Compounds	Linear	20% compounds	50% high NO_3 compounds	65% high NO_3 compounds
	Feed Additives	Linear	0	7% efficacy during grazing – fed to 40% of dairy cows Housing: Efficacy 15% (spring calvers) 25% (autumn calvers) 30% (beef cattle). Fed to 30% of spring calvers, 60% of autumn calvers, 35% of beef cattle.	7% efficacy during grazing to 2028 – 20% post 2028 as halides are fed to 50% of dairy cows Housing: Efficacy 15% (spring calvers) 25% (autumn calvers) 30% (beef cattle). Fed to 40% of spring calvers, 70% of autumn calvers, 45% of beef cattle.
	Lipids in Diet	Sigmoidal	0%	8% (dairy)	15% (dairy)

Sector	Measure	Uptake rate response curve	Current (2018) situation	2030 - Pathway 1	2030 - Pathway 2
	Low Emission Slurry Spreading	Hyperbolic	50%	80% uptake	80% uptake
	Acidification/Amendments	Sigmoidal	0%	11% dairy/pigs 8% other	20% dairy/pigs 10% other
	Slurry Aeration	Sigmoidal		25% dairy/pigs 15% other	40% dairy/pigs 20% other
	Mineral Soil Drainage	Linear		10% of poor-drained land	25% of poor-drained land
	Digestate (biomethane)	Sigmoidal	2000 m^3	520,000 m^3 slurry	3,500,000 m^3 slurry
	Impact of Diversification on Livestock Numbers	Sigmoidal	0	54849 LU reduction (69192 bovines, 11124 sheep)	137963 LU reduction (186929 bovines 198350 sheep)
LULUCF	New Hedgerows	Sigmoidal	0	20,000 km extra	40,000 km extra
	Hedgerow Management	Linear	0	50,000 km	75,000 km
	Grassland Management	Linear	0	505 kha	750 kha
	Water Table Management (Peat soils)	Sigmoidal	0 kha	40 kha	80 kha
	Cover Crops	Linear	1.5 kha	50 kha	75 kha
	Straw Incorporation	Linear	10 kha	60 kha	85 kha
	Manure to cropland	Linear	50 kha	64 kha extra	112 kha extra
	Afforestation	Linear	2kha	8kha to 2030 then 4 kha to 2050	8 kha 20 2050
	Prevent Deforestation	Hyperbolic	752 ha p.a	495 ha p.a.	495 ha p.a.
	Extend rotation to MMAI	Linear	0%	21% of forests	31% of forests

Sector	Measure	Uptake rate response curve	Current (2018) situation	2030 - Pathway 1	2030 - Pathway 2
	Agroforestry	Linear	0%	1 kha	2 kha
	Birch (Raised bogs)	Linear	0 kha	17.9 kha	17.9 kha
Energy	Energy Efficiency	Linear	0.02 TWh	0.5 TWh	0.5 TWh
	Biomethane	Sigmoidal	0.01 TWh	1 TWh	5.7 TWh
	Wood Energy	Linear	2.9 TWh	4.1 TWh	4.1 TWh
	Biomass Crops (heat)	Linear	0.3 kha	15 kha	15 kha
	Biomass Crops (electricity)	Linear	1.5 kha	9 kha	9 kha

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

2.3.1. Agricultural Scenarios

In terms of the Climate Action and Low Carbon Development Act 2021, GHG emissions reductions must be attained relative to that level of GHG emissions in 2018. However, the level of agricultural activity in the coming years will not be the same as in 2018. It is therefore necessary to project the future level of activity and the associated impact on greenhouse gas emissions.

The FAPRI-Ireland partial equilibrium model of the Irish agricultural economy simulates over a medium term (10 year) horizon; the model generates projections of agricultural activity levels, agricultural commodity supply and use balances, agricultural commodity and input prices and generates projections of the economic accounts for agriculture (Donnellan and Hanrahan, 2006). The FAPRI-Ireland partial equilibrium model is linked to the FAPRI EU (GOLD) model (Hanrahan, 2001 and Westhoff and Meyers, 2010) and is similar to models such as the OECD AGLINK model (OECD, 2015) that the OECD and the European Commission use in their respective outlook publications (OECD, 2020; EC 2019).

The FAPRI-Ireland model takes exogenous projections of macroeconomic aggregates (such as GDP growth rates, inflation, exchange rates, populations) from the ESRI COSMO model of the Irish macroeconomy (Bergin et al. 2016). The FAPRI model has been developed and maintained by Teagasc and used to analyse the impact of various agricultural policy and trade issues over the last 20 years, and has over the last decade provided agricultural activity projection to Ireland's Environmental Protection Agency (EPA) that are used in the reporting of GHG emissions under the Monitoring Mechanism Regulation (EC, 2013).

Three alternative Business-As-Usual (BAU) scenarios have been generated by the FAPRI-Ireland model which *exclude mitigation* from additional measures. The scenarios represent S1 the Base case (mid), S2 the low scenario and S3 the high scenario. These scenarios were developed for sensitivity purposes in the reporting of GHG emissions under the Monitoring mechanism Regulation and reflect some of the uncertainty concerning future levels of agricultural activity in Ireland over the period to 2030. The macroeconomic aggregates taken from the ESRI COSMO model and the international agricultural commodity and input prices taken from the FAPRI-EU model are unchanged across the three scenarios. For more detail on these projections see Donnellan and Hanrahan (2006), Binfield et al. (2008), Donnellan and Hanrahan (2006) and Hanrahan (2001) on the FAPRI-Ireland model structure and functioning.

The key driver of agricultural GHG emissions in Ireland continues to be the level of activity in bovine agriculture. The scenarios produced (S1, S2 and S3) differ in terms of dairy and beef (other) cow numbers, associated cattle progeny, land use, N fertiliser use and other inputs.

It is important to emphasise that the projections under each of the three scenarios are not forecasts. The projections are based on a set of differing assumptions concerning future policy conditions and are conditional on projections of future EU and World agricultural commodity market conditions and wider macroeconomic developments. The exclude any adoption of mitigation measures to reduce GHG emissions. The different agricultural activity scenarios (S1, S2 and S3) are presented as an aide to understanding that there is a range of different future potential outcomes for activity levels and associated GHG emissions in the presence of policy and market uncertainty.

The Base case projection is the FAPRI-Ireland Baseline projection, which is aligned with the FAPRI (September 2022) projections for medium terms developments in EU and World agricultural commodity markets. The Baseline assumes that agricultural policy continues as currently agreed and that the Trade and Cooperation (Brexit) Agreement (TCA) reached between the EU and the UK governs UK-EU trade for the period to 20302030. It is further assumed that no new bilateral trade agreements are entered into by either the EU or UK that offers other third countries preferential market access to EU and UK markets (thus, for instance, the impact of recent bilateral trade agreements between the UK and Australia that have not yet been implemented are not incorporated in any of the scenarios modelled).

Climate Policy in Ireland is now governed by an Act of the Oireachtas that has set as a national policy objective a reduction of 51% in emissions of GHG and the establishment of a "climate neutral" economy by 2050. Five yearly sectoral emissions ceilings have been allocated to agriculture and other sectors defined in the Act. However, to date specific agricultural policy schemes specifically designed to alter agricultural activity levels that drive agricultural GHG emission have not been implemented and are not considered under the Base Case or alternative High and Low scenarios.

Because of the uncertainty concerning future economic and policy developments and their implications for variables such as agricultural prices, rates of subsidy and trade tariffs, it is not possible to know future levels of agricultural activity with certainty and by extension future levels of GHG emissions from agriculture are also uncertain.

Over the medium term agricultural policies in Ireland, the EU and our export markets will change. Trade policy and other policies, including those related to the environment, will also change. The macroeconomic environment within which agricultural activity takes place will also change. The 2020 and 2021 Covid-19 pandemic illustrates the impossibility of accurately forecasting the medium term economic outlook in an *unconditional* manner. The inherent policy, market and macroeconomic uncertainty, creates the possibility that future Irish agricultural activity levels, under possible alternative policies, could be very different to what we have in 2022 or 2023. Therefore, as in previous years, we have produced two additional (alternative) scenarios, with higher (High) and lower (Low) levels of the key (bovine) agricultural activities in Ireland over the medium term.

The divergence from the Base (Baseline) case under the Low (S2) and the High (S3) Scenario is driven by differences in the outlook for the key bovine breeding inventories from the outlook under the Base case. The dairy cow and beef (Other) cow inventories, and developments in these activities, are critical to the future development of the total bovine population and to the wider set of agricultural activity levels that drive the impact of agriculture on national GHG emissions.

By contrast, under the Low (S2) scenario the growth in the dairy inventory is slower than under the Base Case and the contraction in the beef cow inventory is stronger than under the Base case. Again these developments are driven by a set of assumptions regarding the economic signals that Irish dairy and beef farms are anticipated to respond to over the medium term. Compared to the Base case these economic signals are more pessimistic in the Low scenario and are reflected within the FAPRI-Ireland economic model by lower level of Bovine and other related agricultural economic activities.

Under the High (S3) Scenario the growth rate in dairy cow inventories over the medium term is higher than under the Base case, while the rate of contraction in the beef cow herd that is projected is slower than under the Base case. The alternative (High) bovine breeding inventory pathways are driven by assumptions regarding the development in the economic incentives to engage in these economic activities (farming dairy and beef cows respectively). In the High scenario we are more optimistic concerning theses economic signals than under the Base case.

Under all three scenarios the same macroeconomic assumptions are used (currency exchange rates, GDP growth and inflation rates). World and EU agricultural commodity market signals are also assumed not to vary across between the three scenarios . The different levels of Irish agricultural commodity production under the S2 and S3 are not assumed to affect the EU or World market prices.

2.3.1.1.S1 Base Case without mitigation

Under the Base case scenario, dairy cow numbers are projected to increase reflecting the expected continuing profitability of dairy production in Ireland. Dairy cow numbers in 2030 are projected to reach 1.691 m (Figure 2.2). This represent an 8% increase relative to 2022. In contrast, the continuing low levels of profitability of beef cow production systems is reflected in a projected ongoing contraction of beef cow inventories. Beef cow numbers in 2030 are projected to decline to 0.632 m, a 29% decrease relative to 2022.

The overall cattle inventory is largely determined by developments in these two breeding inventories, with the level of live exports of (predominantly young) cattle from Ireland being another important determinant of the total bovine population in Ireland. Total cattle inventories under the base case are projected to decline over the period to 2030. By 2030 total cattle numbers are projected to be 6.78M, 5% lower than in 2022.

While total cattle inventories are declining over the projection period, projected growth in dairy cow numbers and contraction in beef cow numbers leads to a change in the composition of the Irish bovine inventory and in the intensity of grassland use. Dairy production systems operate at a higher stocking rate than beef production systems and this higher stocking rate is reflected in higher projected use of nitrogen fertiliser per hectare of Grassland and in increased total aggregate nitrogen fertiliser use by the Irish agricultural sector over the period to 2030. Total nitrogen fertiliser use in 2030 is projected to be 399,156 tonnes. This represent a 16.3% increase relative to 2022. This projected increase in fertiliser use as is clear from Figure 2.3 is reflective of very low levels of fertiliser use in 2022 when the extremely high fertiliser prices, a consequence of the illegal Russian invasion of Ukraine, led to large reductions in fertiliser use. Under the Base case fertiliser prices are projected to return to levels close to those prevailing prior to the war and as a consequence fertiliser use is projected to recover from 2026 onwards.

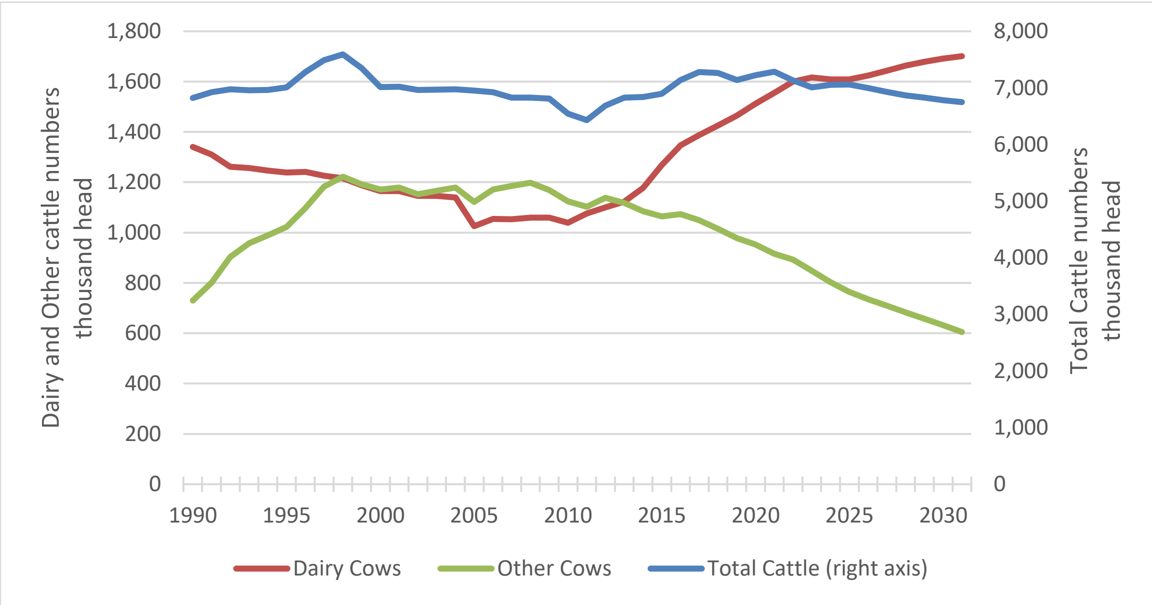
Under the Base case, Irish ewe and total sheep numbers are projected to decline over the period to 2030 due to projected reductions in the price of lamb. By 2030 total Irish sheep numbers are projected to decline to 4.77 m. This represents a 9% decline relative to 2022. This decline is a consequence of a projected decline in the profitability of sheep (and general meat) production over the period to 2030.

The projected decline in margins from sheep production reflects the projected evolution of sheep prices on world and EU markets. Global growth in the supply of meat is expected to outpace growth in demand over the period to 2030. This global supply and use dynamic is reflected in lower world prices for poultry, pig meat, beef and sheep meat. The weak world meat price environment and weak demand growth in the EU (due weak economic growth and trends away from meat consumption by some European consumers) over the medium terms is reflected in lower Irish and EU lamb prices. By 2030 Irish prices are projected to be 23% lower than the record high levels observed in 2022.

Under the Base case the total volume of pig output is projected to be relatively stable. Breeding pig numbers as well as overall pig inventories are projected to decline over the period to 2030 as pig meat prices decline. The decline in Irish pig meat prices reflects developments in global pig meat markets wherein recovering production in China is projected to reduce Chinese pig meat import demand and as a consequence global pig meat prices are projected to decline as the rate of growth in global production exceeds the rate of growth in consumption. Total pig inventories in Ireland in 2030 are projected to be 3% lower than in 2022.

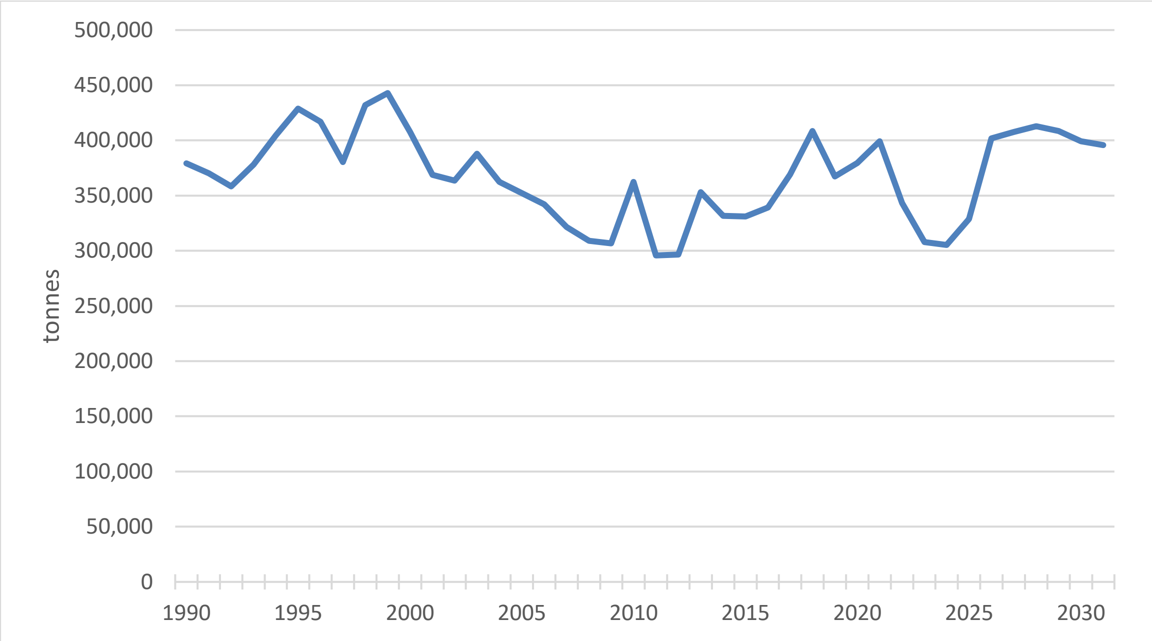
Under the Base case poultry production is projected to continue to grow over the projection period to 2030. Growth in consumption of poultry underpins the continued growth in poultry production in Ireland between 2022 and 2030, but lower poultry prices leads to a considerable moderation in the annualised rate of growth that is projected which at 0.4% is considerable lower than the average rate of growth In production observed over the last decade of 2.6% per annum. By 2030 the total volume of poultry meat output and poultry places are projected to be 5% higher than in 2022.

Under the base case, the total crop land area is projected to contract due to the higher level of profits per hectare in grassland farming (dairying) compared to tillage. By 2030, the total cereal area harvested in Ireland is projected to decrease to 249,500 hectares. This represent an 8% decrease relative to 2022.



Source: Historical data EPA, Projections from 2021 FAPRI-Ireland Model.

Figure 2.1: *Total Cattle, Dairy and Other Cow Inventories 1990-2030 (Base Case S1)*



Source: Historical data EPA, Projections from 2022 FAPRI-Ireland Model.

*Figure 2. 2***:** *Total Nitrogen Fertiliser Sales 1990-2030 (Base Case S1)*

2.3.1.2. Alternative Agricultural Activity Scenarios

Under the Low (S2) Scenario dairy prices are exogenously assumed to be lower than those projected under the Base case, while negative direct payments (taxes) are introduced as a mechanism to incentivise farmers to hold fewer beef cows than under the Base case.

Under the High (S3) Scenario, Irish milk prices are assumed to be exogenously higher and direct payments that are coupled to beef production are introduced to incentivise farmers to hold more beef cows than under the Base case.

Neither of the assumptions regarding higher or lower dairy prices or coupled subsidies (direct payments) or taxes on beef cows that are made under the High and Low scenarios should be interpreted as projections or forecasts of policy changes that could or should happen. They are simply mechanisms to generate alternative outcomes using the FAPRI-Ireland *economic* model, which are useful in assessing the sensitivity of the Base case set of agricultural activity projections.

2.3.1.3. S2 Low Scenario (weaker growth in bovine and related agricultural activity levels)

Under the Low (S2) scenario, Irish milk prices are lower than under the Base case scenario while negative subsidies are introduced to the model, so that the retention of beef (Other) cows is dis-incentivised. These two assumptions reduce the economic incentives to farm both beef cows and dairy cows and as a result the level of total cattle inventories and other related agricultural activities (e.g. fertiliser use) are lower than under the Base case scenario.

Despite the lower level of Irish milk prices, Irish dairy cow numbers are still projected to slightly increase under the S2 scenario relative to observed levels in 2022. This increase reflects the continuing profitability of dairy production in Ireland even at the lower path for milk prices that is assumed under the Low scenario. Dairy cow numbers in 2030, under the Low scenario, are projected to reach 1.629 m. This represent a 2% increase relative to 2022. However, the projected inventory for 2030 represents a decline relative to the projected inventory for 2030 under the Base Case.

Under the Low scenario (S2), beef cow numbers in 2030 are projected to decline to 0.457 m. This represent a 49% decrease relative to 2022.

Under the Low scenario, total cattle inventories are projected to decline over the projection period. Total cattle inventories in 2030 are 6.313 m. This represent a 10% decrease relative to 2022.

Under the Low (S2) scenario, the rate of contraction in beef cow numbers is more significant than under the Base case. Even though the total cattle population is falling, the dairy share of this population is increasing and the higher stocking rate on dairy farms partially offsets declining stocking rates on beef farms. Total use of nitrogen decreases initially under this scenario due to the projected high price of fertiliser. However, over the period 2026 to 2030 the price of fertiliser is projected to return to close the levels observed prior to Russia's invasion of the Ukraine. At more "normal" fertiliser price levels, the effect of the decline in beef cow inventories and total cattle inventories dominates the evolution of per hectare and aggregate fertiliser use. By 2030 the total use of Nitrogen is 360,641 tonnes. This represent a 5% increase relative to the relatively low levels of fertiliser use in 2022. Total fertiliser use under the Low scenario is projected to be 9% lower than under the Base case.

Under the Low scenario, lower economic returns to beef farming lead to further declines in beef cow inventories. While returns to sheep relative to beef improve, and ewe and total sheep numbers under the Low scenario are projected to be marginally higher than under the Base case, over the period to 2030 Irish ewe and sheep numbers are still projected to decline. By 2030 sheep numbers are projected to decline to 4.83 m a 7% decline on 2022 levels.

Projections for pig and poultry production under the Low scenario are not different from those under the Base case. Pig and poultry production activity in Ireland is not a significant user of agricultural land and Irish pig and bird prices are largely determined by developments in EU and world markets. These factors mean that the changes in bovine activity (beef and dairy) that characterise the Low scenario are not projected to lead to changes in the level of agricultural activity associated with pig and poultry production.

In the Low scenario, total cropland is projected to contract at a slower rate than under the Base case scenario. The decline in the returns of both dairy and beef compared to tillage crops means that while land under crops declines, the rate of contractions is lower than under the Base case. By 2030, the total cereal area harvested in Ireland declines to 258,046 hectares. This represent a 5% decrease relative to 2022.

2.3.1.4. S3 High Scenario (stronger growth in bovine and related agricultural activity levels)

Under the S3 scenario, higher milk prices are projected to result in a 23% increase in dairy cows to 1.76 million by 2030 relative to 2018. Conversely, suckler cow numbers are projected to decrease by 26% to 720,000 by 2030. This results in a total bovine population of 7.01 million bovines by 2030, a 3% decrease relative to 2018. This stronger increase in dairy cow numbers also results in higher mineral nitrogen fertiliser application compared to S1 and S2. Therefore, by 2030, 421 ktonnes N is projected to be applied, which represents a 6% increase relative to 2018. Sheep, pig and poultry numbers are projected to be the same as under the S1 scenario.

2.3.1.5. Summary of scenario activity levels and associated GHG emissions

Taking the overall levels of activity for all of the agricultural sectors (including nitrogen use) across all of the scenarios analysed, allowed for the projection of GHG emissions under the Baseline (S1) and across the two other scenarios (Figure 2.1). All totals were collated using NIR 2021 Inventory emission factors. The GHG emissions associated with each scenario by 2030 was 21.95 $MtCO_2e\ yr^{-1}$ (S1), 21.07 $MtCO_2e\ yr^{-1}$ (S2) and 22.79 $MtCO_2e\ yr^{-1}$ (S3). Therefore, by 2030, the span across the three scenarios amounted to 1.72 Mt $CO_2e\ yr^{-1}$. Across all three scenarios, the proportional contribution of each gas remained constant, with methane comprising 70% of total emissions, while N_2O and CO_2 contributed 25% and 6% of total GHG emissions respectively.

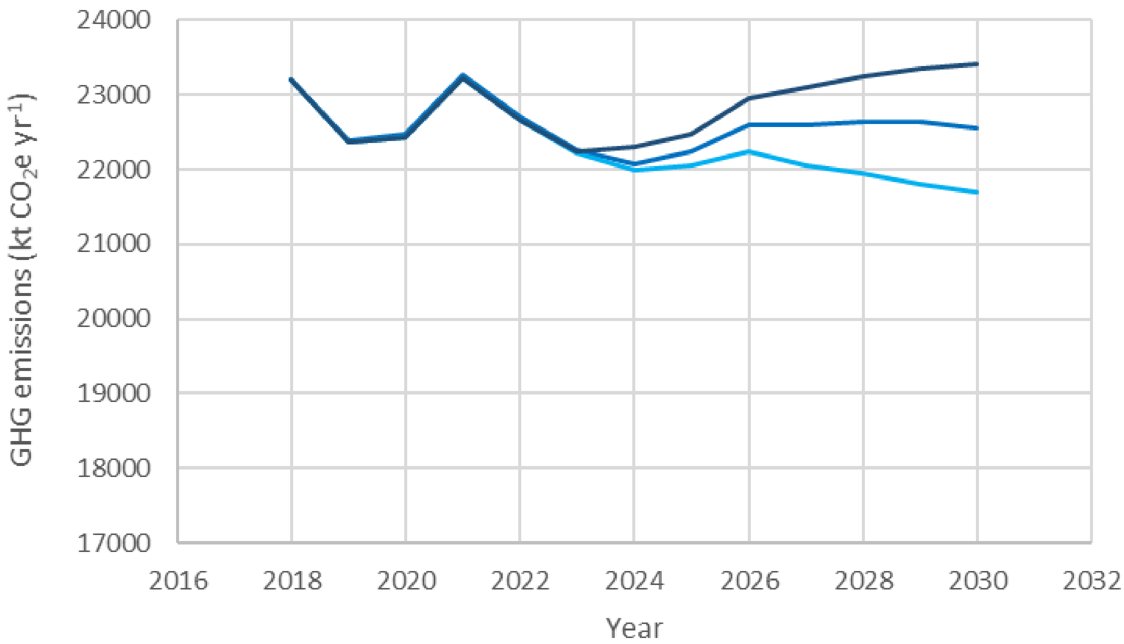


Figure 2. 3: Projected GHG emissions associated with S1, S2 and S3 activity scenarios.

2.3.2. LULUCF Projections

Projections of LULUCF sources and sinks were made using a) the amount of cropland and grassland projected by the FAPRI model and using Tier 1 land-use factors currently utilised in the National Inventory Report. Sequestration rates for forestry were calculated by Kevin Black of FERS Ltd., using the CBM-CFS3 Model. Under a Business-as-Usual scenario, using gross-net reporting, LULUCF would be a net source of 9.93 $MtCO_2e\ yr^{-1}$ by 2025 and a source of 10.5 $MtCO_2e\ yr^{-1}$ by 2030 (Table 2.2). This increase in emissions is due to three principal causes. Firstly, Ireland has legacy effects of both agriculture and peat extraction on organic soils resulting in substantial emissions (over 9 Mt $CO_2e\ yr^{-1}$ in the grassland category and 2.5 Mt $CO_2e\ yr^{-1}$ in the wetland category) that are both highly uncertain in terms of both geographical extent and emissions per unit area. However, the area of peat assumed to be drained is due to be substantially revised from the current 329kha to between 90-120 kha. This would effectively reduce this emission source by 6 $MtCO_2e\ yr^{-1}$ (Tuohy et al. 2023).

Secondly, the age profile of Irish forestry is such that a large proportion of the current forest stock (circa 18%) has reached maturity and is due to be harvested over the period to 2030, resulting in a substantial diminution of the forestry sink. Thirdly, Ireland also has legacy-related issues in terms of the large cohort of forestry on organic soils. Between 1950 and 1990, around 200,000 ha of forestry was planted, primarily on public land, by the state forestry board, Coillte (Black et al. 2008). Since the mid-80's, subsidised private planting became more common and between 120,000 ha and 195,000 ha of forestry on organic soils has been planted since 1990 (Renou-Wilson et al. 2018, Connolly 2018). As a result of these historical actions, Ireland now has the highest percentage of forestry on organic (blanket peat and fen) soils in Europe. In more recent afforestation programmes, the policy of planting on peats has changed to recognise the wider biodiversity functions of these areas. In addition, new research on forested organic soils shows larger emissions than previously estimated. Furthermore, there is a clear trend of increasing emissions from older forest land established in the 1950's and 1960's due to afforested peatlands becoming a net emission source after 1-3 rotations (Hargraves et al., 2003). As a legacy issue, there are limited interventions open to redress these emissions under the current regulations.

It should be noted that the rehabilitation and restoration of 33,000 ha of peatland formerly used for industrial extraction is included in the BAU. The reason for this is that implementation of this measure occurred prior to 2020.

Table 2. 2: Projections of LULUCF emissions from 2021 to 2030.

BAU	Current Baseline for net-net	**2016-18**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
New Afforestation			0.002	0.002	-0.003	-0.012	-0.025	-0.042	-0.063	-0.087	-0.115	-0.147
Managed Forest Lands (FL-FL)[1]			-0.43	0.36	1.09	2.49	2.07	3	2.58	2.73	3.04	2.83
Existing Afforested Lands (L-FL)			-1.61	-1.82	-1.99	-2.43	-1.95	-2.18	-1.87	-1.79	-1.84	-1.61
Total forest land (Incl. HWP)		-3.03	**-2.04**	**-1.46**	**-0.90**	**0.05**	**0.10**	**0.78**	**0.65**	**0.85**	**1.09**	**1.07**
Defor to settlement and other			**0.36**	**0.36**	**0.36**	**0.35**	**0.35**	**0.36**	**0.36**	**0.36**	**0.35**	**0.35**
Cropland (CL)**	0.01	-0.072	**-0.01**	**0.01**	**0.13**	**-0.08**	**0.01**	**-0.15**	**0.1**	**0.03**	**-0.11**	**0.1**
Grassland (GL)**	6.8	6.978	**7.33**	**7.3**	**7.27**	**7.25**	**7.22**	**7.2**	**7.2**	**7.19**	**7.18**	**7.17**
Wetlands (WL)**	2.2	3.182	**2.34**	**2.24**	**2.16**	**2.08**	**1.98**	**1.91**	**1.83**	**1.74**	**1.66**	**1.58**
Settlements		0.16	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.21**	**0.21**	**0.21**
Other		0.05	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Total		**7.27**	**8.25**	**8.72**	**9.28**	**9.92**	**9.93**	**10.36**	**10.41**	**10.43**	**10.43**	**10.54**
Net-net total		-1.95	-1.388	-0.918	-0.353	0.288	0.295	0.728	0.767	0.803	0.805	0.913
EU Reg. Target trajectory*		7.27	7.06	7.02	6.97	6.93	6.89	6.85	6.81	6.76	6.72	6.68

BAU	**2016-18**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
New Afforestation		0.002	0.002	-0.003	-0.012	-0.025	-0.042	-0.063	-0.087	-0.115	-0.147
Managed Forest Lands (FL-FL)[1]		-0.43	0.36	1.09	2.49	2.07	3	2.58	2.73	3.04	2.83
Existing Afforested Lands (L-FL)		-1.61	-1.82	-1.99	-2.43	-1.95	-2.18	-1.87	-1.79	-1.84	-1.61
Total forest land (Incl. HWP)	-3.03	**-2.04**	**-1.46**	**-0.90**	**0.05**	**0.10**	**0.78**	**0.65**	**0.85**	**1.09**	**1.07**
Defor to settlement and other		**0.36**	**0.36**	**0.36**	**0.35**	**0.35**	**0.36**	**0.36**	**0.36**	**0.35**	**0.35**
Cropland (CL)*	-0.072	**-0.01**	**0.01**	**0.13**	**-0.08**	**0.01**	**-0.15**	**0.1**	**0.03**	**-0.11**	**0.1**
Grassland (GL)*	6.978	**7.33**	**7.3**	**7.27**	**7.25**	**7.22**	**7.2**	**7.2**	**7.19**	**7.18**	**7.17**
Wetlands (WL)*	3.182	**2.34**	**2.24**	**2.16**	**2.08**	**1.98**	**1.91**	**1.83**	**1.74**	**1.66**	**1.58**
Settlements	0.16	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.21**	**0.21**	**0.21**
Other	0.05	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Total	**7.27**	**8.25**	**8.72**	**9.28**	**9.92**	**9.93**	**10.36**	**10.41**	**10.43**	**10.43**	**10.54**
EU Reg. Target trajectory	7.27	**7.06**	**7.02**	**6.97**	**6.93**	**6.89**	**6.85**	**6.81**	**6.76**	**6.72**	**6.68**

[1] Based on forestry projections provided by K. Black, FERS Ltd using the same approaches used for the Irish NFAP 2021-2030. * based on the formula used for the option 1.2 target (pg 85 of the amended EU LULUCF regulations (July 2021)) and the 2020 LULUCF inventory submissions from Ireland and the EU.

3. Overall MACC Results and Recommendations

3.1. Total Mitigation Potentials

Achieving both 2025 and 2030 sectoral targets as well as delivering carbon neutrality by 2050 will be extremely challenging for the agriculture, forestry and land-use (AFOLU) sectors.

Mitigation of greenhouse gases was divided into four parts: a) emission intensity measures which help reduce the carbon footprint of agricultural produce, b) measures that reduce absolute agricultural emissions of methane and nitrous oxide, c) carbon sequestration via LULUCF measures and d) offsetting GHG emissions in the Energy sector via fossil fuel displacement from bioenergy. New measures, not previously included in the 2018 MACC assessment, include new fertiliser types, reduced age of finishing, the inclusion of lipids and feed additives in bovine diets, slurry amendments/aeration during storage as well as hedgerows and forestry management. All the mitigation values shown in the sections below are based on the S1 activity levels (see Section 2) and represent the mitigation potential in 2030.

3.2. Agricultural Mitigation

3.2.1. Emission Intensity Measures under S1

’Emission intensity’ measures mainly comprised cost-negative measures, such as animal health and animal breeding which concurs with the previous 2012 and 2018 analysis. These measures principally improve the GHG efficiency of the system and thus directly reduce the emissions intensity of meat and milk but only *indirectly* reduce methane and/or nitrous oxide by reducing the number of animals required to produce a given amount of meat or milk. Two measures, dairy EBI and extended grazing has both an efficiency component and an absolute reduction component. The EBI is a single figure profit index that identifies the most profitable bulls and cows for breeding (Berry & Ring 2020). It favours animals whose progeny have a long herd life, produce high quantity and quality of milk within a 365-day calving interval, calve easier and have progeny who themselves will calve easily in the future and exhibit large carcass weights. Higher EBI herds, thus, have longer milking periods, produce more milk solids and require fewer replacements, all of which reduce the C footprint. As a result, in the absence of further EBI improvement, 155,000 extra cows would be required to deliver the same amount of milk solids projected to be produced by 2030. Improved animal health also reduces the need for dairy or beef replacements by reducing mortality, improves milk and milk solid production per animal and improves liveweight gain, while improved beef breeding improves fertility, ease of calving and liveweight gain. Extended grazing reduces absolute methane emissions as a) there is reduced manure to be stored and managed and b) cattle grazed on fresh grass have lower methane emissions compared to those fed grass-silage (O’Neill et al. 2012, Cummins et al. 2022).

However, animal health and beef breeding measures also contribute to reducing the age of finishing, which *does* reduce absolute GHG emissions. In addition, higher EBI dairy cows have been shown to have lower associated methane yields (Y_m) compared to lower EBI cows and thus a component of EBI delivers ‘absolute’ GHG mitigation. As these measures are associated with breeding and animal health, they are incremental over time. The efficiency measures consisted of dairy EBI, animal health, extended grazing and beef breeding measures (maternal and terminal indices). The total cost-negative 'efficiency' abatement was estimated at 1,524 kt CO_2e yr^{-1} for the Pathway 1 uptake scenario by 2030 (Figure 3.1) and 1,955 kt CO_2e yr^{-1} for the Pathway 2 uptake scenario by 2030 (Figure 3.2). The cumulative savings associated with all efficiency measures was estimated to be between €527 million and €578 million per annum by 2030. The majority of GHG mitigation of C footprint was observed to be attributable to two measures: Dairy EBI and animal health, which together accounted for 82% and 85% of total mitigation across Pathways 1 and 2 respectively (Figure 3.1).

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 expected improvement in emissions intensity. In this case, any reductions attributable to improved emissions intensity of produce would be partially, 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 emissions 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 improvement in EBI, associated milk solid production per cow and an increase in dairy cow and dairy farm numbers has led to a 68% increase in milk production between 2012 and 2020 (Kelly et al. 2020). This has resulted in a 12% increase in total GHG emissions but also an 8% decrease in the carbon footprint.

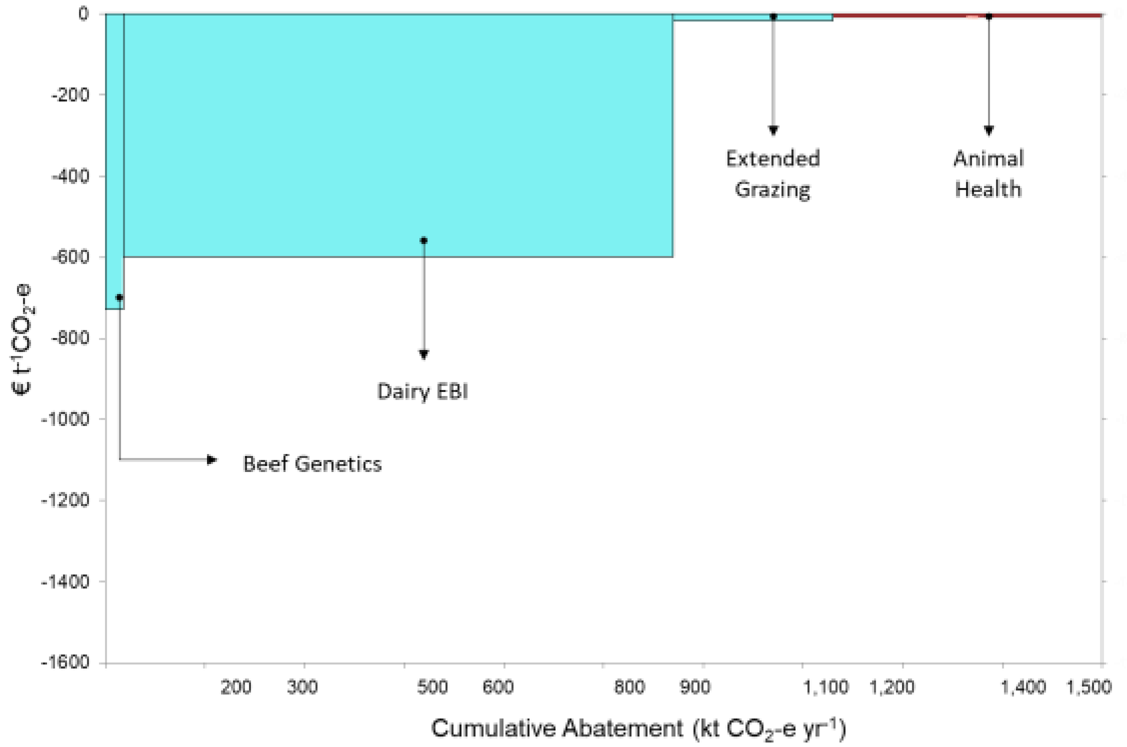


Figure 3.1: Marginal Abatement Cost Curve for emission intensity measures for Scenario 1 activity levels under Pathway 1 Uptake Rates. Values represent the maximum yearly abatement in 2030. Dashed line indicates the carbon price.

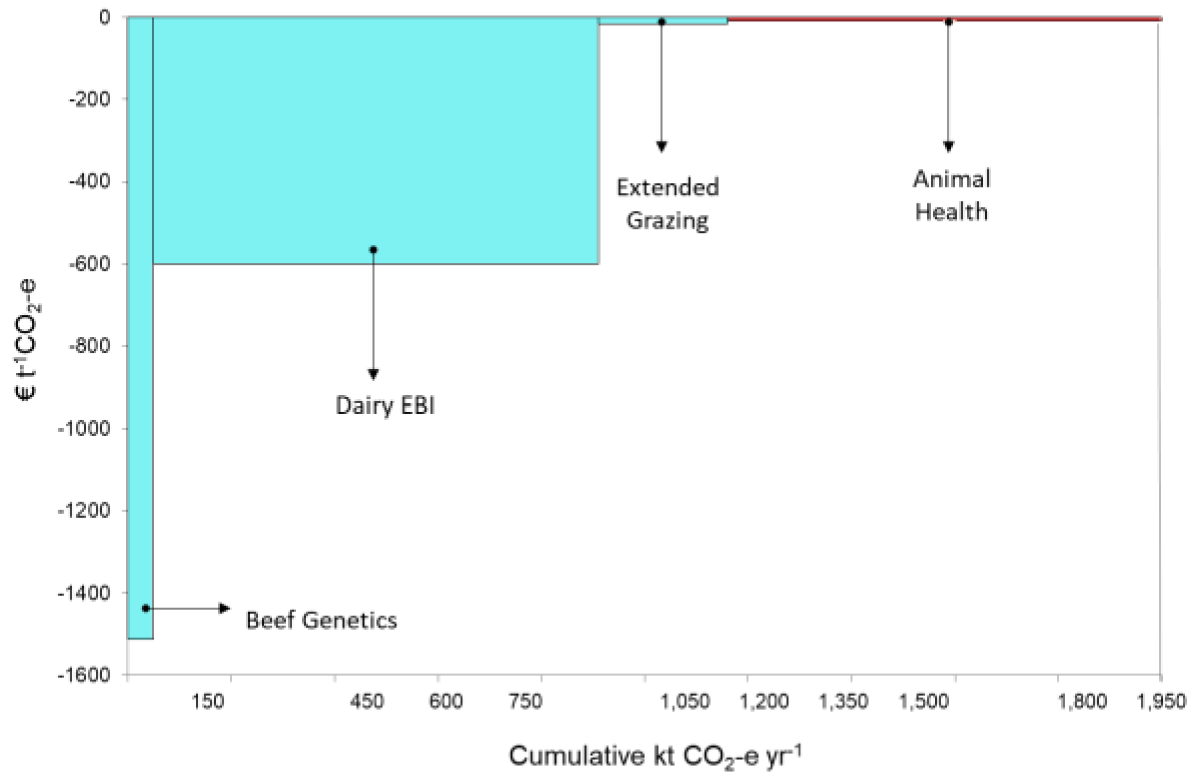


Figure 3.2: Marginal Abatement Cost Curve for efficiency measures for Scenario 1 under Pathway 2 Uptake Rates. Values represent the maximum yearly abatement in 2030.

3.2.2. Measures (absolute) that directly reduce Agricultural GHG emissions under S1 activity

Data presented in the following section principally utilise the S1 activity scenario, due to the fact that, a) this is considered the most likely trajectory of Irish agriculture over the remainder of the decade and b) as such is the scenario used by Irish Inventory compilers in the Environmental Protection Agency to generate sectoral emissions projections that are submitted to the EU. A separate sub-section (3.2.3) addresses mitigation potential under the S2 and S3 activity scenarios.

'Absolute' mitigation measures have been defined in this report as those measures that impact on total activity (e.g. fertiliser amount) or on emission factors (GHG emissions associated with a given quantum of an activity). Thus, these measures directly reduce GHG emissions associated with a given activity. A full description of each measure, its efficacy, uptake rate assumptions and speed of uptake for the three scenarios and pathways 1 and 2 are presented in Section 4 and associated tables in Appendix 1.

By 2030, the S1 mitigation potential for both pathways was projected to rise to a maximum abatement total of 2,820 ktCO_2e yr^{-1} (Pathway 1, Figure 3.3) or 4,857 ktCO_2e yr^{-1} (Pathway 2, Figure 3.4). The net marginal abatement costs ranged from -€1,776 per tonne CO_2e abated for Dairy EBI (under both Pathways) to +€399 per tonne CO_2 abated for the drainage of wet mineral soils (Pathway 1, Figure 3.3) or +€325 per tonne CO_2e abated for phosphorus impact on N_2O emissions (Pathway 2, Figure 3.4).

Unlike the 'emission intensity' measures, no one measure was observed to dominate the mitigation potential, with individual measures delivering, on average 6% each of the total emission reduction. For Pathway 1 uptake, the most cost-beneficial measure was reducing the age of bovine finishing, which delivered 470 kt CO_2e yr^{-1} in 2030 and cumulatively 2371 kt CO_2e across the entire 2021-2030 period (Figure 3.1, Table 3.1). This equated to 18% of total mitigation and was cost negative in terms of marginal abatement cost (-€130 $t^{-1}CO_2$e). Over the period 2010 to 2020, there has been substantial progress made in reducing the age at which bovine animals are finishinged in Ireland and it is projected that a mean 90 day reduction in finishing age could be achieved over the remainder of the decade.

The other principal measures for Pathway 1, in terms of delivering cumulative reductions across the entire period, were altered fertiliser formulation (14%), dairy EBI (12%) and the use of clover and multi-species swards (8%). Collectively, these measures comprised 53% of total emissions reduction. It should be noted that the fertiliser formulation measure comprises three sub-measures:

1) The substitution of Calcium Ammonium Nitrate (CAN) and straight urea with Urea coated with the urease inhibitors, NBPT, NPPT or 2NPT (Harty et al 2016, Roche et al. 2016)
2) The replacement of high nitrate compounds (eg. 27-2.5-5) with ammonium-based compounds (Rahman & Forrestal 2021, Gebremichael et al. 2021)

3) The substitiution of Calcium Ammonium Nitrate with Urea coated with the urease inhibitors and a nitrification Inhibitor incorporated into the granule (Pathway 2 only)

Since publication of the last MACC, major progress has been made in the development of nutritionally based solutions to reduce enteric methane emissions (Lahart et al. 2021 ,Roskam et al., 2023, Kirwan et al. 2023). These feed additives include, 3-Nitrooxypropanol, (3-NOP), a synthetic non-toxic organic compound that inhibits the final step in methanogenesis (Duin et al., 2016). Supplementation has been shown to result in a 30% methane yield decrease in many trials across the world, mainly within indoor settings (Martinez-Fernandez et al., 2014; Haisan et al., 2017; Romero-Perez et al., 2014; Jayanegara et al., 2018; Kirwan et al., 2023).

By 2030 the use of feed additives to reduce methanogenesis, primarily during the housing period, or introduced during milking, is projected to deliver 396 ktCO_2e yr^{-1} or 14% of annual mitigation at a cost of between €88 - €166 t$^{-1}CO_2$e.

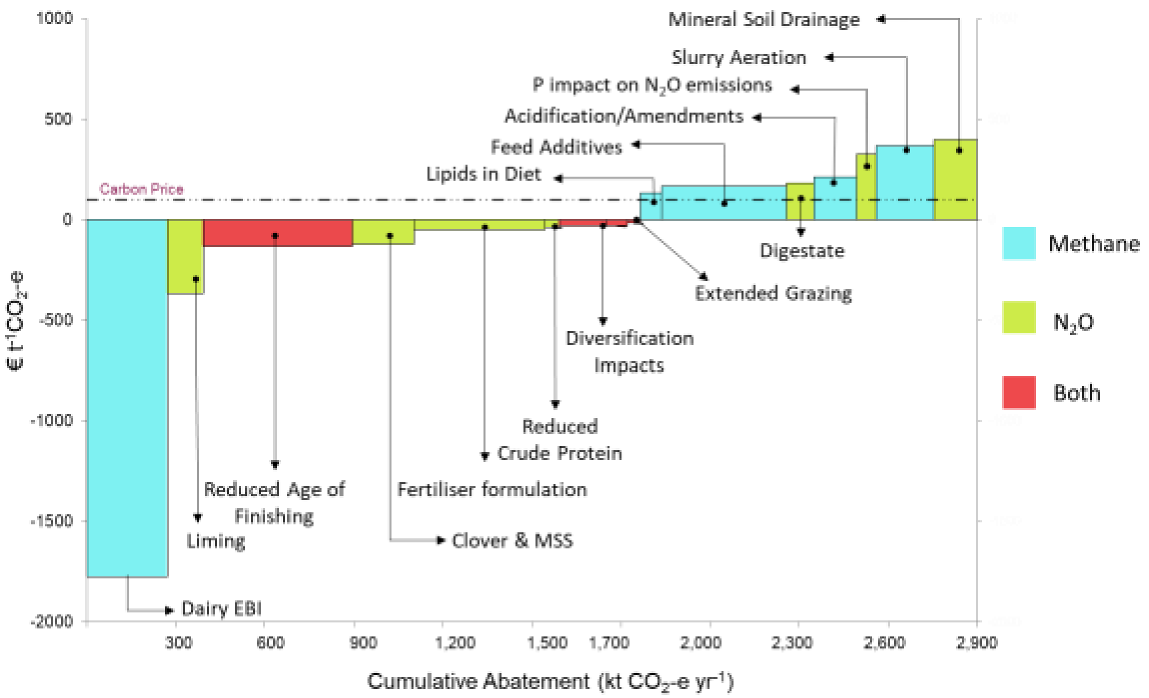


Figure 3.3: Marginal Abatement Cost Curve for agriculture measures under Scenario 1 with Pathway 1 Uptake Rates. Values represent the maximum yearly abatement in 2030. Dashed line indicates Carbon cost of €100 per tonne CO_2.

Under Uptake Pathway 2, reduced age of finishing is again the most impactful measure and comprises 3649 ktCO_2e over the 2021-30 period or 15% of total mitigation potential and reaching a maximum of 732 ktCO_2e yr^{-1} by 2030 (Figure 3.4, Table 3.1). The other principal measures were fertiliser formulation, diversification impacts and feed additives. These four principal measures comprised 49% of total mitigation.

- The diversification measure comprises bovine and ovine displacement due to increased diversification into organic farming, forestry but especially growing feedstock for biomethane production. The principal difference between pathways 1 and 2 for this measure is that under Pathway 1, 26 kha of grassland is required, whereas under Pathway 2, 150 kha is required. Assuming a 50% reduction in stocking rate, these diversification measures could have the potential to displace between 54,000 LU and 138,000 LU comprising both cattle and sheep.

- The greater abatement potential of the feed additives under Pathway 2, is due to the assumption that the feeding of halides to bovines will be available by 2028. This feed additive has the potential to reduce methane emissions associated with grazing by 20% compared to 7% upon feeding with 3-NOP, which is assumed in Pathway 1 (Connolly et al. 2023).
- Reduced age of bovine finishing and fertiliser formulation comprise the other two measures that deliver >10% of the total emissions reduction (13% and 11% respectively).

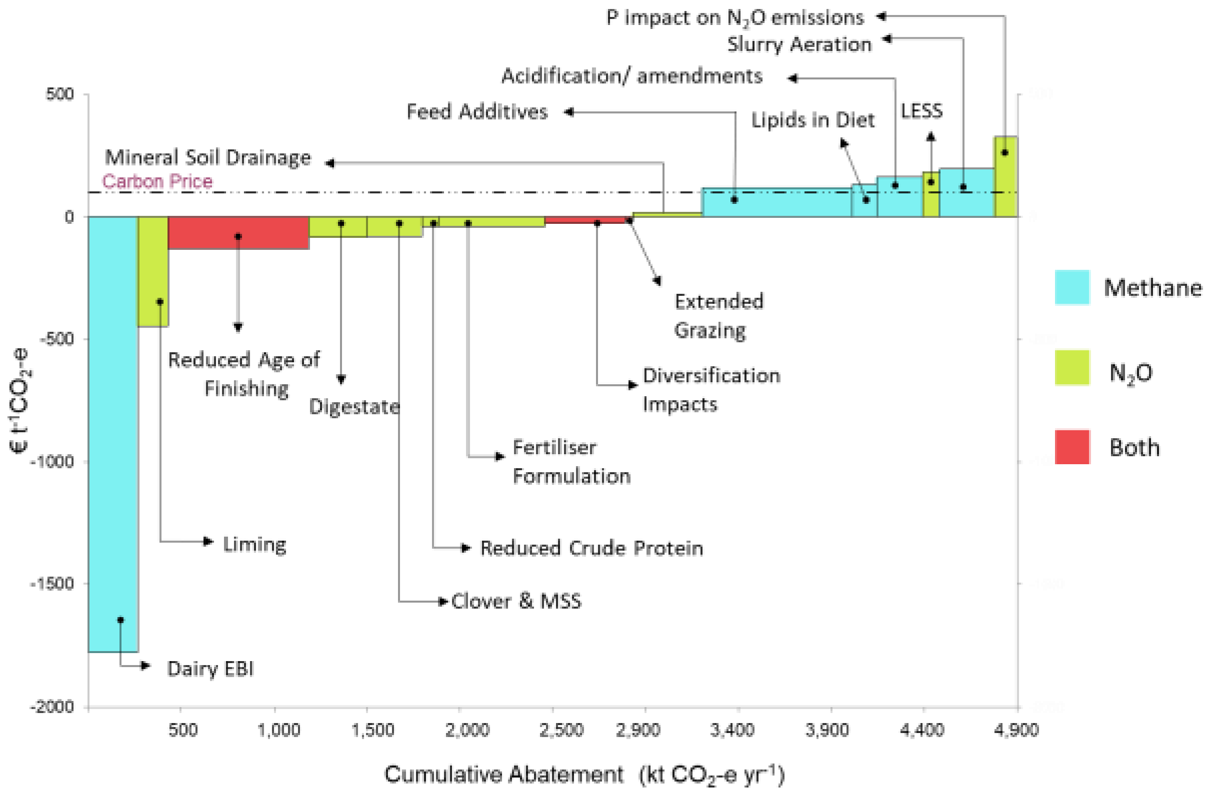


Figure 3.4: Marginal Abatement Cost Curve for agriculture measures under Scenario 1 with Pathway 2 Uptake Rates. Values represent the maximum yearly abatement in 2030. Dashed line indicates Carbon cost of €100 per tonne CO_2.

In terms of reduction per gas, the mitigation of methane comprised 51.5% of total mitigation and N_2O comprised 48.5% of the total. The big difference is that the N_2O measures are ready to be deployed and the majority of these measures have linear or front-loaded uptake (in the case of LESS). In contrast the methane measures were mainly assigned a sigmoidal uptake response as many of the measures are new (e.g. Feed additives) or need infrastructure or demonstration/advisory investment (e.g. Acidification, lipids, digestate).

In terms of cost-effectiveness, 1,741 ktCO_2e yr^{-1} (Pathway 1) and 3,591 MtCO_2e yr^{-1} (Pathway 2) or 62% and 69% of the total abatement potential were under €100 t^{-1} CO_2e abated (Figure 3.3, 3.4). The most costly measures were mineral soil drainage, low emission slurry spreading and P impact on N_2O emissions. Drainage is extremely sensitive to the spacing between drains, and increasing gravel mole spacing from 1m to 2m decreases the costs by 60%. Adequate P is a requirement for successful implementation of the clover/legume measure and thus has co-benefits. Additionally, the high cost of LESS when expressed per tonne CO_2e abatement can be misleading as, while this measure does not mitigate much GHG emissions, it provides over 50% of ammonia mitigation, and is relatively cheap from an ammonia abatement perspective (see Buckley et al. 2020). The remaining costs-positive measures are all methane-reducing measures. These measures (feed additives, lipids in diet, aeration and acidification of slurry) are technically costly and have no resource saving (unlike N measures, which defray fertiliser costs).

Nine of the sixteen measures listed here were cost-negative, particularly dairy EBI, which accounted for between 67% and 82% of the total cost savings, depending on Uptake Pathway and cost pathway assumptions (Table 3.1). Dairy EBI had potential cost savings of up to €450M per annum by 2030. The remainder of the cost savings was principally due to either increased margins associated with reducing the age of finishing or the reduced need for mineral fertiliser associated with N saving measures. This was particularly apparent under the high costs scenario, where the monetary savings from reduced fertiliser use were proportionately greater than the increased fixed costs or fuel costs for some measures. This resulted in lower net costs in some cases under a high cost scenario. For example, the marginal abatement cost associated with clover/multi-species swards was -€26 t^{-1}CO_2e and +€12 t^{-1}CO_2e for Pathways 1 and 2 respectively under the low cost assumptions, where the price of N fertiliser was set at €1.20 and fuel at €0.53 per litre. However, under a high cost scenario, the marginal cost savings rose to -€79 t^{-1}CO_2e and -€120 t^{-1}CO_2e despite fuel prices increasing to €1.30 per litre and 12% increases in seed cost, due to higher savings in terms of N fertiliser costs which rose to €2.60 per kg N.

The total projected expenditure for cost-positive measures by 2030 was between €178M and €256M for Pathway 1 and €264M and €315M for Pathway 2 (Table 3.1). In contrast, the cost of methane measures increased under the high cost scenarios. For feed additives, aeration and dietary lipids, the cumulative costs under the S1 Pathway 1 were €1.2m and €43.9m for Carbon Budget periods 1 and 2, respectively under the low cost scenario and €1.2m and €50.7m M under the high cost scenario. Under S1 pathway 2, the costs scaled with the abatement reduction and costs increased to €1.3m (Carbon Budget 1) and €63.4m (Carbon Budget 2) for low cost scenario and €1.7m (Budget Period 1) and €94.5m (Budget Period 2) for the high cost scenario. The highest cost variability was observed for drainage of mineral soils measure, with costs varying from +€57M to -€100M. This measure was particularly sensitive to the balance between extra grass growth obtained following drainage and drainage costs.

In terms of timing of costs, over 70% of the gross expenditure was projected to occur during the second carbon budget. This was due to the fact that many of the (technical) measures assumed a sigmoidal rate of uptake (e.g. feed additives, aeration, acidification, protected urea+ nitrification inhibitor, dietary lipids) with the majority of cumulative abatement occurring during the Carbon Budget 2 period.

Table 3. 1: Cumulative agricultural abatement, maximum annual abatement in 2030 and associated cumulative cost range for a) two levels of uptake (Uptake Pathways 1 and 2) two levels of costs (Low and High Cost scenario).

Measure	**Cumulative Mitigation 2021-30 ($ktCO_2e$)**	**Cumulative Cost 2021-30 (€ M)**			**Annual Mitigation (2030) ($ktCO_2e\ yr^{-1}$)**	**Annual Cost (2030) (€ M)**		
Pathway 1								
Reduced Age of Finishing	2371	-309	to	-240	470	-€61.2	to	-€47.5
Fertiliser Type	1901	-22	to	-67	418	-€7.1	to	-€19.5
Dairy EBI	1561	-2254	to	-1701	255	-€453.7	to	-€342.4
Clover & MSS	1063	-27	to	-128	193	-€5.0	to	-€23.3
Feed Additives	964	85	to	140	396	€39.0	to	€65.7
Slurry Aeration	821	230	to	230	182	€67.3	to	€28.8
Diversification Impacts	818	-25	to	-25	150	-€4.5	to	-€4.5
Low Emission Slurry Spreading	772	281	to	230	87	€31.7	to	€67.3
Mineral Soil Drainage	742	-246	to	289	145	-€49.2	to	€57.8
Acidification/Amendments	572	77	to	140	136	€26.0	to	€15.9
Liming	381	-92	to	-188	112	-€18.7	to	-€40.8
Reduced Crude Protein	316	-28	to	-9	45	-€5.0	to	-€1.6
Lipids in Diet	270	31	to	41	67	€5.9	to	€8.9
Phosphorus Impact on N2O emissions	219	48	to	71	58	€12.8	to	€18.9
Digestate (biomethane)	182	1	to	-5	64	€0.4	to	-€1.9
Extended Grazing	181	-3	to	-2	41	-€0.6	to	-€0.5
Total	**13134**	**-2253**	**to**	**-1223**	**2820**	**-€422.1**	**to**	**-€218.9**
Pathway 2								
Reduced Age of Finishing	3649	-€476	to	-€240	732	-€95.3	to	-€66.7
Fertiliser Type	2616	-€35	to	-€106	553	-€6.1	to	-€20.9
Diversification Impacts	2231	-€60	to	-€60	417	-€11.1	to	-€11.1
Feed Additives	1745	€116	to	€195	788	€53.9	to	€92.6
Mineral Soil Drainage	1630	-€501	to	€34	363	-€100.3	to	€6.9
Clover & MSS	1574	€347	to	-€124	286	€63.0	to	-€22.6
Dairy EBI	1561	-€2,254	to	-€1,701	255	-€453.7	to	-€342.4
Slurry Aeration	1173	€325	to	€141	286	€95.0	to	€39.4
Acidification/Amendments	985	€128	to	€140	245	€35.7	to	€15.9
Digestate (biomethane)	872	-€22	to	-€63	308	-€10.0	to	-€24.9
Low Emission Slurry Spreading	772	€281	to	€192	87	€31.7	to	€55.8
Liming	553	€7	to	-€316	162	€1.9	to	-€72.6
Reduced Crude Protein	545	-€60	to	-€23	93	-€10.8	to	-€3.9
Lipids in Diet	514	€60	to	€78	125	€11.0	to	€16.6
Phosphorus Impact on N_2O emissions	441	€97	to	€144	116	€25.6	to	€37.8
Extended Grazing	181	-€3	to	-€2	41	-€0.6	to	-€0.5
Total	**21041**	**-€2,051**	**to**	**-€1,711**	**4857**	**-€370.0**	**to**	**-€300.7**

Mitigation Under Scenarios 2 and 3

The lower activity levels under Scenario S2 and higher activity levels under Scenario S3 resulted in 2030 emissions that were 4.3% lower and 4.0% higher respectively (see Section 2). The mitigation measures scaled with the changes in activity levels (Table 3.2).

Table 3. 2: *Cumulative agricultural abatement and maximum annual abatement in 2030 for the low (S2) and high (S3) activity scenario under a) two levels of mitigation measure uptake (Uptake Pathways 1 and 2).*

Activity Scenario/Measure	**Pathway 1**		**Pathway 2**	
Scenario S2	**Cumulative mitigation 2021-2030 (kt CO_2e)**	**Mitigation in 2030 (Kt CO_2e)**	**Cumulative mitigation 2021-2030 (kt CO_2e)**	**Mitigation in 2030 (Kt CO_2e)**
Reduced Age of Finishing	2306	450	3518	705
Fertiliser Type	1846	400	2522	533
Dairy EBI	1524	244	1505	246
Feed Additives	1123	438	2057	871
Clover & MSS	1036	185	1517	276
Diversification Impacts	796	143	2151	402
Slurry Aeration	795	174	1131	276
Low Emission Slurry Spreading	757	83	744	84
Mineral Soil Drainage	721	139	1571	350
Acidification/Amendments	553	130	949	236
Liming	367	107	533	156
Reduced Crude Protein	269	36	525	90
Phosphorus Impact on N_2O emissions	212	56	426	112
Extended Grazing	176	39	175	40
Digestate (biomethane)	175	61	841	296
Total	12655	2686	20163	4673
Scenario S3				
Reduced Age of Finishing	2963	489	4595	785
Fertiliser Type	2310	434	3148	570
Dairy EBI	2103	265	2133	263
Clover & MSS	1378	201	2065	295
Feed Additives	1222	476	2220	931
Low Emission Slurry Spreading	1132	90	1153	90
Diversification Impacts	1026	156	2300	430
Slurry Aeration	933	189	1331	295
Mineral Soil Drainage	910	151	1969	374
Acidification/Amendments	619	141	1100	252
Liming	388	116	563	167
Reduced Crude Protein	373	39	701	96
Phosphorus Impact on N2O emissions	240	60	486	120

Extended Grazing	212	43	213	42
Digestate (biomethane)	193	67	926	317
Total	16000	2917	24902	5028

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 24%-32% 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 increased use of 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 emissions avoided due to lower fertiliser 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 1.2 Mt CO_2-e yr^{-1}.

Similarly, under IPCC rules, the GHG and land-use impacts associated with soybean and imported maize production are not included in the GHG emission of Irish agriculture, although emissions from meal production are circa. 800 kgCO_2-e per tonne meal produced (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.

3.2.4. The Use of the GWP* Alternative Metric in order to Calculate Emissions and Mitigation Potentials

Global Warming Potential is a measure of how much heat (infrared radiation, IR) that a unit of a greenhouse gas will trap in the atmosphere over a specified period (usually 100 years) relative to the amount of IR radiation that will be trapped by the same amount of carbon dioxide (CO_2). The GWP of a gas also takes into account the length of time the gas remains in the atmosphere. Each GHG is thus expressed using CO_2 equivalents, which is the time-integrated radiative forcing of a quantity or rate of gas emissions to the troposphere. This value is calculated by multiplying the mass of gas by its GWP.

However, each GHG not only varies in terms of radiative forcing, but also in terms on mean atmospheric residence time. Long lived GHG's such as N_2O and CO_2 last between 100 and 5,000 years in the atmosphere. However, short-lived climate pollutants (SLCP's) such as HFC's and methane have mean residence times from a few hours (SF_6, HFC's) to 12 years (methane).

A new usage of GWPs, denoted GWP*, allows emissions of short-lived and long-lived climate pollutants (SLCP & LLCPs) to be more consistently expressed within a single metric by equating a change in the emission rate of an SLCP as equivalent to a single emissions pulse of a long-lived pollutant. Unlike the traditional GWP metric, which only takes into account the radiative forcing of a given greenhouse gas over a set time frame (usually 100 years), GWP* takes into account the total amount of energy imbalance between the Earth and space caused by the emissions of a given gas .As originally defined in Allen, et al. (2017) a step-change in emission rate of an SLCP (ΔSLCP tonnes per year) is equivalent to a one-off pulse emission of ΔSLCP × GWPH × H tonnes of CO_2, where GWPH is the conventional Global Warming Potential relative to CO_2, integrated over a time horizon H years. This was further refined by Cain et al. (2019) which modified GWP* to account for the fact that the climate does not respond instantly to changes in radiative forcing. This was resolved by the incorporation of a term for each of the short-timescale (*r*) and long-timescale climate responses (*s*) to changes in atmospheric SLCP concentrations. Calculated using this re-defined GWP*, with the metric CO_2 *warming* equivalents (CO_2-we) emissions of an SLCP in a given year are defined:

$$E_{CO2}we = \left(r \times \frac{\Delta E_{SLCP}}{\Delta t} \times H + s \times E_{SLCP}\right) \times GWP_H \quad (1)$$

where GWP_H is the conventional global warming potential for a given SLCP over time-horizon H (100 years), ΔE_{SLCP} is the change in SLCP emission rate over the preceding Δt years, E_{SLCP} is the SLCP emissions for that year, and r and s the weights assigned to the rate and stock contributions, respectively. The two weighting factors depend on the representative concentration pathway (RCP) scenarios used but Cain et al. (2020) demonstrated that using the GWP100 and a combination of r and s of 0.75 and 0.25 respectively matched historical and projected warming impacts of methane over a range of emission trajectories. The term Δt spreads the SLCP pulse emission rate over Δt. Although Δt should equate to the mean residence time of methane (12 years), Allen et al. (2017) suggested at least 20 years, as shorter timespans can produce volatility in the emissions profile and ≥ 20 years improved the correspondence with temperature response. Smith et al. (2021) proved that 20 years corresponded to the instantaneous radiative forcing impact of the release of one tonne of methane relative to that of CO_2 and further refined the metric to include a scaling factor *g*, which adjusted values to match this initial gradient associated with a pulse of CH_4.

The FAPRI projections, along with the mitigation calculated in Sections 3 and 4 were used in order to generate BAU GWP* emissions, as well as emissions following implementation of either of the mitigation pathways. The results are shown in Figure A3.1. BAU emissions when expressed in GWP* terms were observed to be more variable compared to conventional GWP. GWP* emissions were lower than GWP between 2008 and 2020. This relative decrease was due to reduced methane emissions post-CAP reform in 1998 and reflected the decreased methane due to deceased sheep numbers during that period. The impact of the g scaling factor refinement on GWP* introduced by Smith et al (2021) increased GWP* by circa. 7.4 MtCO-we and resulted in higher total emissions compared to those generated using conventional GWP. However, the impact of mitigation was also amplified, with Pathway 1 delivering 22% reduction in emissions by 2030 relative to 2018, while Pathway 2 mitigation reduced GWP *emissions by 77% (Figure 3.5). This would mean that Pathway 1 measures would almost deliver the full 25% reduction required under the sectoral targets.

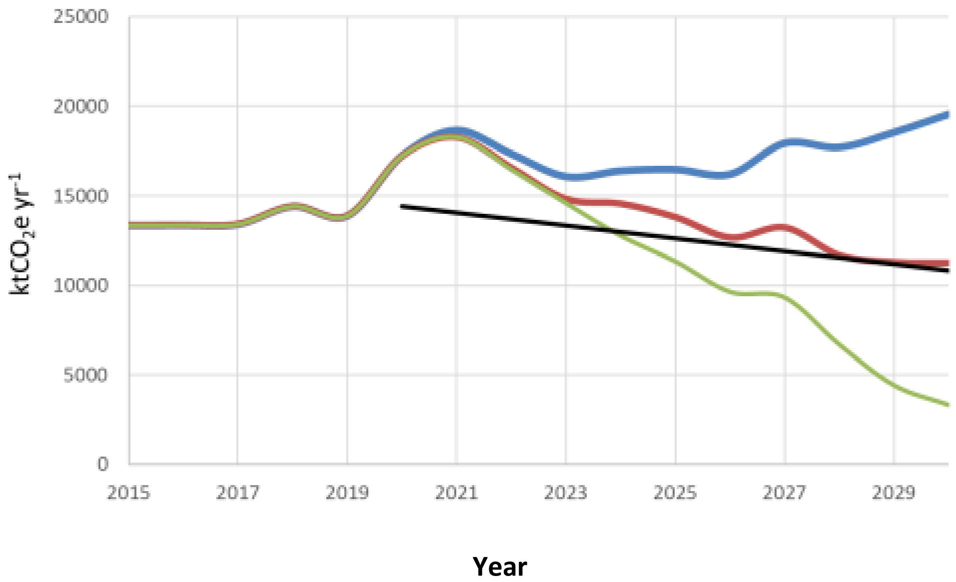


Figure 3. 5: *BAU emissions expressed using GWP (dashed line), GWP* (blue line), GWP* with Pathway 1 (red line) and GWP* with Pathway 2 mitigation (green line).*

3.2.6. Impact of GWP* on individual MACC measures

GWP* amplified the level of methane mitigation compared to GWP-100. Under GWP-100, methane and N_2O abatement comprised circa 50% each. Under GWP*, methane abatement rose to 81% of total mitigation potential. When expressed on a GWP-100 basis, methane abatement measures would result 1.76 $MtCO_2e\ yr^{-1}$ (moderate pathway) and 2.69 $MtCO_2e\ yr^{-1}$ (enhanced pathway) by 2030. This equates to an 11.6% and 17.6% reduction in total methane for the moderate and enhanced mitigation pathways respectively. However, when GWP* is used, the abatement potential rises to 8.58 $MtCO_2e\ yr^{-1}$ (moderate pathway) and 10.88 $MtCO_2e\ yr^{-1}$ (enhanced pathway) by 2030, equating to a 50.1% and 63.5% reduction for the moderate and enhanced mitigation pathways respectively. When expressed on a GWP* basis, this means that all the methane abatement measures come in at under €50 per tonne CO_2. Notably, acidification, feed additives and lipid supplementation abatement costs lowered from €102 $t^{-1}CO_2$, €114 $t^{-1}CO_2$ and €142 $t^{-1}CO_2$ to €26.83 $t^{-1}CO_2$, €28.17 $t^{-1}CO_2$ and €35.17 $t^{-1}CO_2$ respectively (Figure 3.6).

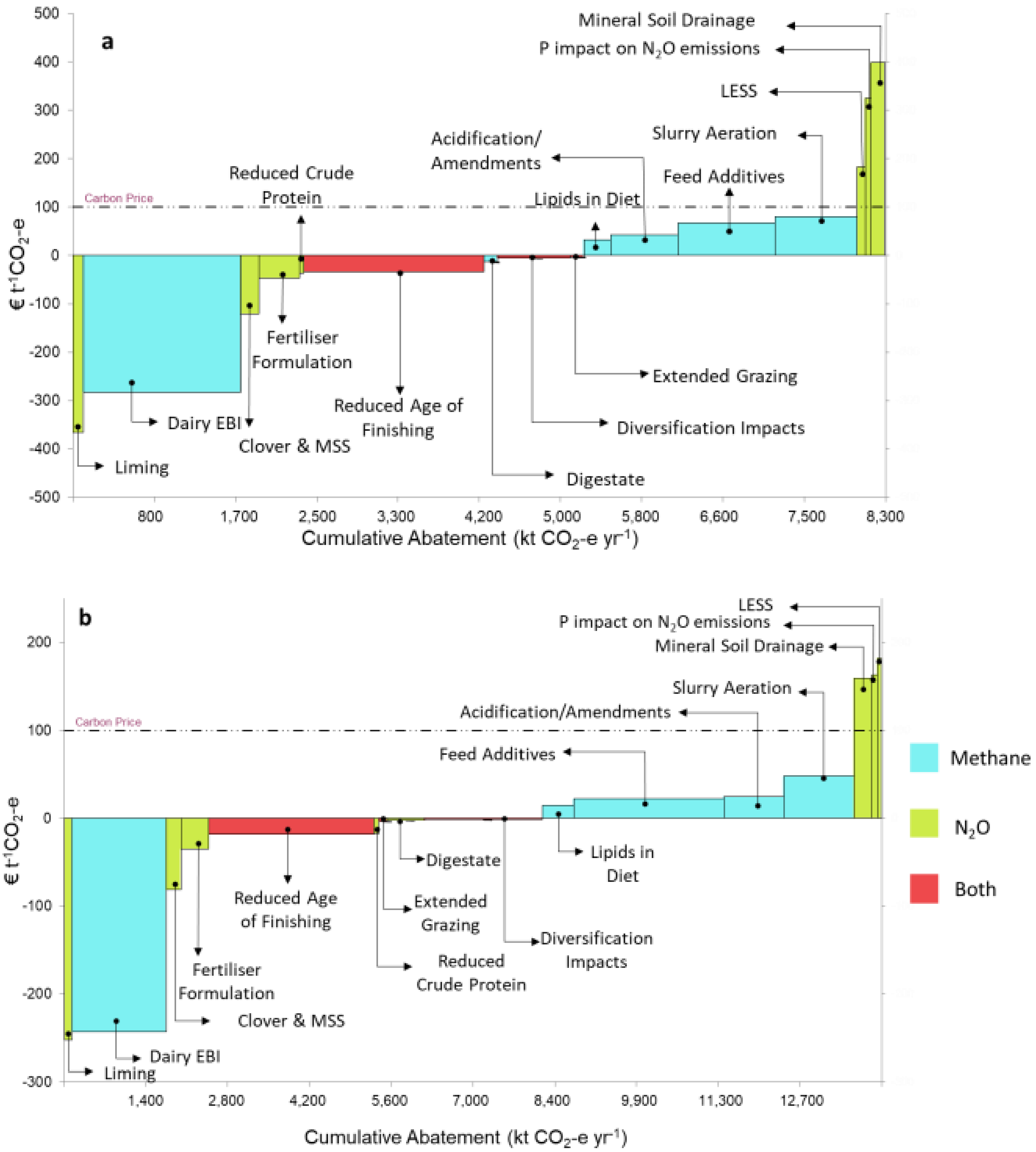


Figure 3.6: Marginal Abatement Cost Curve for methane and N_2O mitigation measures under a) Pathway 1 and b) Pathway 2 when methane was expressed on a GWP basis*

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

The quantum of LULUCF mitigation was much more uncertain than agricultural mitigation. This is due to large uncertainties in terms of both land-use/land-management factors (i.e. the amount of carbon gained lost in response to a land-use or land management change) and the area/status of various land categories (e.g. the extent and drainage status of peat soils). In particular, the pathways for the inclusion of mineral grassland management into the inventory is much less clear compared to croplands, peatlands or grassland on peat soils. In contrast, sequestration/mitigation associated with forestry has a clear path in terms of inventory inclusion as afforestation and forest management already operates at a Tier 3 level.

In terms of increasing removals or decreasing emissions from the LULUCF sector, there were a number of mitigation options available over the commitment period and these are shown in Figure 3.7 and Figure 3.8. In the short term, accelerated forestry planting would deliver only modest reductions; a cumulative 762 ktCO_2e over the 2021-2030, with 286 ktCO_2e yr^{-1} under both pathways by 2030 (Table 3.3). Nevertheless, increased afforestation will be required in order to obtain significant reductions in AFOLU emissions in the 2030-2050 period. Reductions in deforestation would result in reductions in LULUCF emissions of 140 ktCO_2e yr^{-1} for each year of the commitment period, resulting in over 1 Mt CO_2e abatement over the entire period (Figure 3.7, 3.8, Table 3.3). It should be noted that a level of deforestation will be required in peatland areas and for windfarms to achieve current renewable energy targets. The main contribution of forestry towards 2030 targets would be to delay clearfelling until the timber volume Mean Maximum Annual Increment (MMAI) is achieved. Current management practice of conifer forest adopts a commercial rotation age, which is 30 to 40% less than the age at MMAI of spruce and pine crops. This means that crops are currently harvested before maximum productivity is reached. Extension of rotation age to MMAI has been shown to increase CO_2 sequestration in the Coillte estate (Black et al., 2022). However, implementation of an extended rotation policy to the national estate was limited to 21%-31% due to windthrow and other silvicultural constraints. In addition, delayed harvest could impact the industry in the short term; both in terms of feedstocks for sawmills and delayed income for landowners.

The presented extension of rotation age assumes the lengthening of rotation age in either 21% (Pathway 1) or 31% (Pathway 2) of mature forests. This measure would deliver 379 ktCO_2e yr^{-1} for Pathway 1 and 890 ktCO_2e yr^{-1} for Pathway 2 by 2030. However, it would deliver more abatement earlier in the decade (see Table 3.2) and cumulative abatement over the two budgetary periods was estimated to be 4479 ktCO_2e and 7862 ktCO_2e at 21% MMAI (Pathway 1) and 31% MMAI (Pathway 2) respectively. This measure includes the transformation to continuous cover forestry measures and represents the most likely practical implementable pathway to reduce emissions from managed forest lands. Other management solutions, such as agroforestry or replanting forested peat areas with birch will deliver very little to 2030. Further analysis in Section 4 details the impact of these measures to both 2030 and 2050.

There is limited scope to increase cropland measures due to the small size of the sector. Under Pathway 1, 60kha of tillage land has straw re-incorporated into the soils while Pathway 2 has 85kha (25% of all tillage land) straw incorporation. In terms of the use of cover crops, this area is projected to expand by 50kha (Pathway 1) to 75 kha (Pathway 2). However, the main options for enhancing net LULUCF balance from agricultural soils for the period (2021-2030) will be in terms of a) reducing CO_2 emissions from agriculture on organic (peat) soils, and b) increasing carbon removals on grassland on mineral soils via improved nutrient management. Under Pathway 1, 40 kha of grassland on peat soils is placed under modified management, while circa 750 kha of mineral grassland is placed under enhanced nutrient management. Under Pathway 2, over 1 Mha of mineral grassland is placed under enhanced nutrient management and 80 kha of grassland on peat soils is placed under modified management. However, the inclusion of these measures will depend greatly on inventory refinement in terms of moving to Tier 2 grassland and cropland land management factors. Furthermore, both the area of grassland under peat soil AND the drainage status of these soils is highly uncertain. Whilst the national inventories assume that there is 339 kha of peat grassland and that all of it is drained, a compilation of archival reports on drainage works in Ireland indicates that the actual area drained may be no greater than between 80 and 100 kha (Tuohy et al. 2023). Therefore the Adoption Pathway 2 peat soil target of altering the water table on 80 kha may represent 80% of all drained peat soils. Both ambition levels compares favourably with Scotland, where the aim is to rehabilitate 250,000 ha of the over 1 million ha of peatland and England, which are aiming for a 10% rehabilitation target by 2030.

Recent research has quantified the impact of hedgerow planting and hedgerow management on GHG balance (Black et al. 2022). Under Pathway 1, 20,000 km of new hedgerows would be planted and 50,000 km would undergo reduced management, which would sequester an extra 71 $ktCO_2e\ yr^{-1}$ and 229 $ktCO_2e\ yr^{-1}$, respectively. Pathway 2 would double the values of both hedgerow planting and hedgerows under reduced management, resulting in 142 $ktCO_2e\ yr^{-1}$ and 379 $ktCO_2e\ yr^{-1}$ extra sequestration for new and managed hedgerows, respectively.

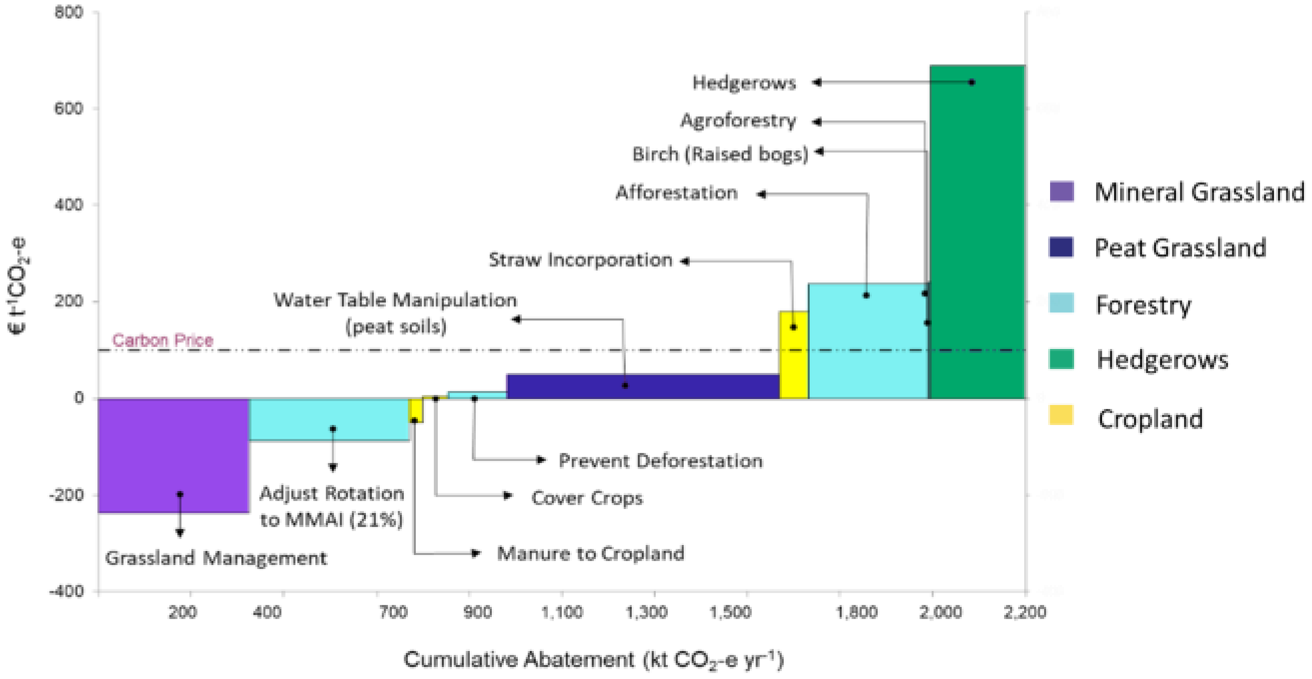


Figure 3.7: Marginal Abatement Cost Curve for LULUCF in 2030 (carbon abatement and sequestration associated with forestry, land management and land-use change) for Pathway 1 uptake levels. Values are based on linear uptake of measures between 2021-2030. Dashed line indicates Carbon cost of €100 per tonne CO_2.

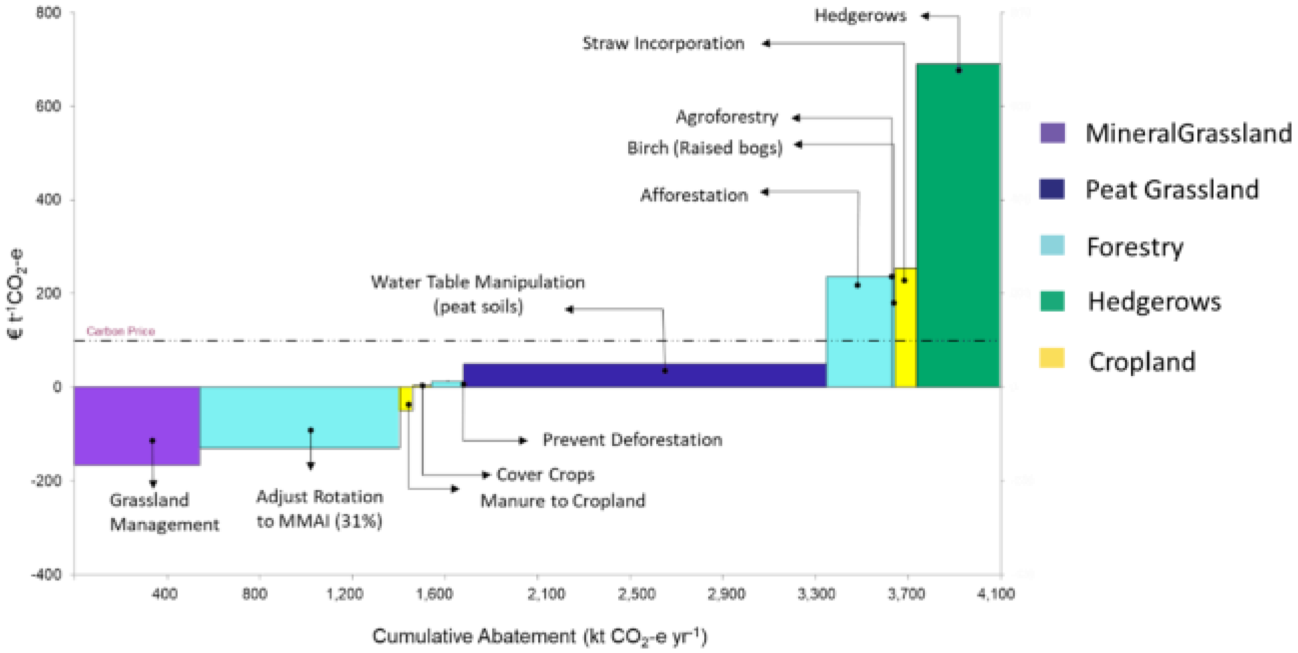


Figure 3.8: Marginal Abatement Cost Curve for LULUCF in 2030 (carbon abatement and sequestration associated with forestry, land management and land-use change) for Pathway 2 uptake levels. Values are based on linear uptake of measures between 2021-2030. Dashed line indicates Carbon cost of €100 per tonne CO_2.

3.3.1. Mean annual and total achievable mitigation and net total costs

The mean annual mitigation in 2030, are projected to be 2,202 $ktCO_2e\ yr^{-1}$ for Pathway 1 and 4,118 $ktCO_2e\ yr^{-1}$ for Pathway 2 (Figure 3.7, 3.8). The marginal abatement cost varied between

-€237 $t^{-1}CO_2e$ to +€689 $t^{-1}CO_2e$ (Pathway 1) and -€166 $t^{-1}CO_2e$ to +€866 $t^{-1}CO_2e$ (Pathway 2), with grassland management associated with the lowest marginal costs and and hedgerow installation associated with the highest costs. The mean marginal costs for uptake Pathway 1 ranged for €75 $t^{-1}CO_2e$ to €92 $t^{-1}CO_2e$ and those for Pathway 2 ranged from €97 $t^{-1}CO_2e$ to €107 $t^{-1}CO_2e$.

Net cumulative costs ranged from €147M to €305M for Pathway 1 and €278M to €280M for Pathway 2 (Table 3.3). By 2030, annual costs were projected to b e€ 111 M to €170 M for Pathway 1 and €259M to €84M for Pathway 2. The reason that the cumulative value was relatively low compared to the projected 2030 expenditure was due to the fact that sectoral cumulative costs were greatly defrayed by large cost savings associated with the extension in rotation age. The cumulative cost savings over both budgetary periods ranged from €394M for Pathway 1 to just over €1000M for Pathway 2 (Table 3.3).

The extension of mature forest to MMAI was the single most impactful measure. However, it should be noted that achieving 31% MMAI would be challenging due to a) an increased risk of windthrow, b) a delay in terms of income for the landowner with delayed harvest (although final harvests would be greater) and c) potential reductions in supply of feedstocks to sawmills. Currently forestry owners harvest before MMAI for a variety of reasons and thus incentives would be required to encourage owners of suitable forests to extend the harvest rotation.

The second most impactful measure is raising the water table on agricultural peat soils (Table 3.2), delivering 2,909 $ktCO_2e$ yr^{-1} for uptake Pathway 1 and 6,504 $ktCO_2e$ yr^{-1} for uptake Pathway 1. This is a cost-positive measure with costs ranging from €20.9m to €67.8m from 2023-2030 depending on drainage cost assumptions and the uptake Pathway. However, a number of key uncertainties remain in terms of agricultural peat soil emissions. The current inventory assumes that all agricultural peat soils (339 kha) are drained and that the mean emission rate is circa 20 tCO_2e ha^{-1} yr^{-1}. It also assumes that no cropland occurs on peat soils. The area of agricultural peatland, the extent of the actively drained area and the associated emissions are, thus, all highly uncertain. The publication of the EPA's new land cover map in conjunction with new research investigating historical peat drainage may reduce the fully drained area of agricultural peatland to 90-120 kha (Tuohy *et al.* 2023). The emissions associated with agricultural peatlands are currently being quantified by the National Agricultural Soil Carbon Observatory (NASCO) and associated projects (Carbosol, RePeat, Terrain AI). However, recent studies in the UK and Ireland have shown a linear relationship between water-table depth and associated soil CO_2 emissions (Evans et al 2021, Aitova et al. 2022).

The third largest abatement measure, sequestration on grassland associated with mineral soils will also require inventory refinement in order to incorporate the modelled additional sequestration into national inventories. This will require the development of land management factors associated with grassland management and these factors are currently being quantified by NASCO in association with the VistaMilk SFI Centre and the Terrain AI

Platform. The cumulative modelled abatement was estimated to be 1,714 ktCO_2e and 2,687 ktCO_2e between 2021-2030 for Pathway 1 and 2, respectively.

There was a similar variation in costs between measures and uptake pathways compared to agricultural abatement. The principal drivers for the difference in net costs between the low and high cost scenarios was the cost savings associated with grassland sequestration, which involved achieving good soil nutrient status. This reduced N fertiliser requirement considerably and this saving was much greater in the high cost scenario. In addition, fuel savings for the hedgerow management and straw incorporation measures were amplified under the high cost scenario. The largest costs were the cost of forest and hedgerow planting, which were the largest expenditures in both scenarios.

Table 3.3: *Cumulative LULUCF abatement and associated costs for a) two levels of uptake (Uptake Pathways 1 and 2) two levels of costs (Low and High Cost scenario).*

Pathway 1	**Cumulative Mitigation 2021-30 ($ktCO_2e$)**	**Cost Range €M**		**€M**	**2030 Mitigation ($ktCO_2e\ yr^{-1}$)**	**2030 Cost €M**		**€M**
mm rotation to **MMAI** 21%	4479	-394	to	-394	379	-33.3	to	-33.3
Water Table Management (Peat soils)	2909	131	to	145	646	29.2	to	32.3
Grassland Management	1714	-135	to	-432	358	-27.7	to	-85.0
Prevent Deforestation	1120	15	to	15	140	1.8	to	1.8
Hedgerows	777	389	to	519	229	118.2	to	157.9
Afforestation	762	180	to	180	287	67.6	to	67.6
Straw Incorporation	345	64	to	65	67	12.6	to	12.0
Cover Crops	325	4	to	1	58	0.8	to	0.3
Birch (Raised bogs)	197	47	to	47	-2	-0.5	to	-0.5
Manure to cropland	120	-2	to	-6	32	-0.4	to	-1.6
Agroforestry	24	6	to	6	7	1.8	to	1.8
Total	***12772***	***305***	***to***	***147***	***2202***	***170.1***	***to***	***-110.7***
Pathway 2								
Extend rotation to MMAI 31%	7862	-1022.0	to	-1022.0	890	-115.6	to	-115.6
Water Table Management (Peat soils)	6504	293.3	to	325.0	1616	72.9	to	80.8
Grassland Management	2687	-93.3	to	-428.1	556	-21.5	to	-92.4
Hedgerows	1283	780.4	to	1042.5	379	237.2	to	316.9
Prevent Deforestation	1120	14.7	to	14.7	140	1.8	to	1.8
Afforestation	762	179.8	to	179.8	287	67.6	to	67.6
Straw Incorporation	465	64.4	to	118.0	95	12.6	to	24.2
Cover Crops	436	5.9	to	1.9	87	1.2	to	0.4
Manure to cropland	206	-2.6	to	-10.2	56	-0.7	to	-2.8
Birch (Raised bogs)	197	46.6	to	46.6	-2	-0.5	to	-0.5
Agroforestry	48	11.6	to	11.6	15	3.5	to	3.5
Total	***21569***	***278.7***	***to***	***279.7***	***4118***	***258.6***	***to***	***283.9***

3.4. Energy: Offsetting fossil fuel emissions

The capacity for offsetting fossil fuel emissions is highly uncertain. In the previous 2018 MACC, bioenergy was estimated to deliver 1.37 to 2.05 Mt CO_2-e yr^{-1}, yet much of this has remained unrealised as both the land area of biomass crops and anaerobic digestion uptake has been very low. In the new 2023 MACC, the annual mitigation potential in 2030 was calculated to be between 2,195 kt CO_2-e yr^{-1} (Pathway 1 Figure 3.9) and 3,303 kt CO_2-e yr^{-1} (Pathway 2 Figure 3.10). This was primarily met by using forestry thinnings in heat and power generation, and a significant amount of manure and grass-based anaerobic digestion (between 1.0 TWe for Pathway 1 and 5.7 TWe for Pathway 2). These two measures accounted for 85% of the total mitigation potential. In addition, 24,000 ha of biomass crops, mainly short rotation coppice (SRC), would be needed for both electricity and heat generation.

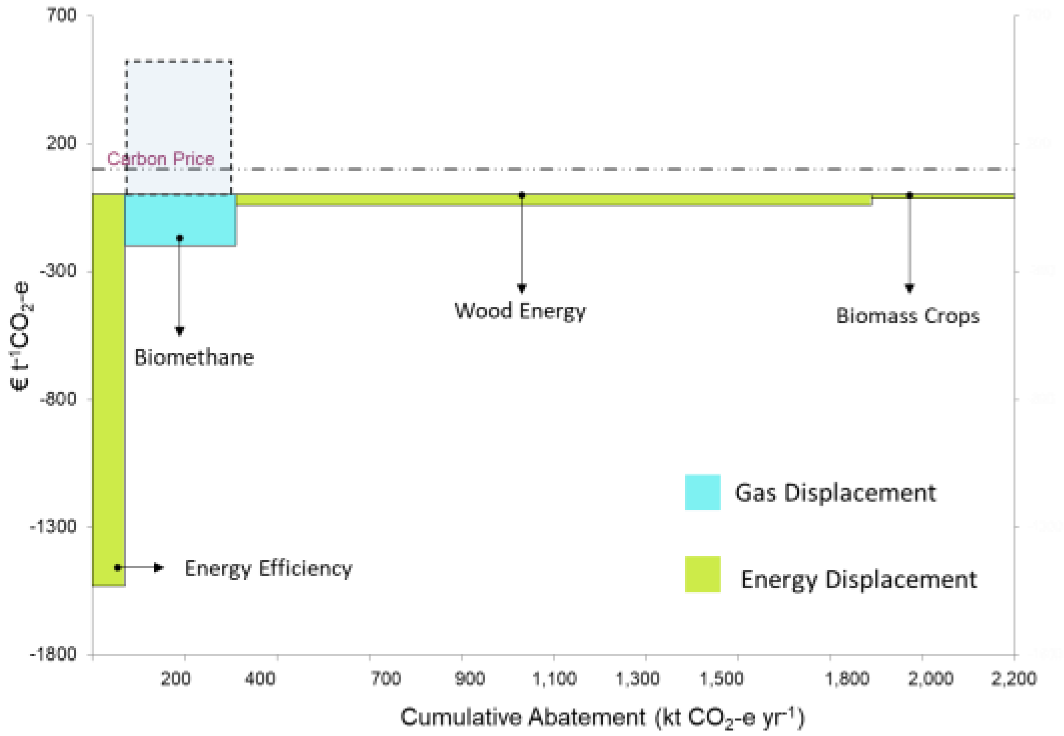


Figure 3.9: *Marginal Abatement Cost Curve for 2030 bioenergy abatement produced in the agriculture and forestry sectors using Pathway 1 uptake levels. Values are based on linear or sigmoidal uptake of measures between 2021 and 2030, and represent the mean yearly abatement over this period. The dashed column indicates the biomethane marginal cost at pre-2022 energy price levels (low cast scenario). Dashed line indicates Carbon cost of €100 per tonne CO_2.*

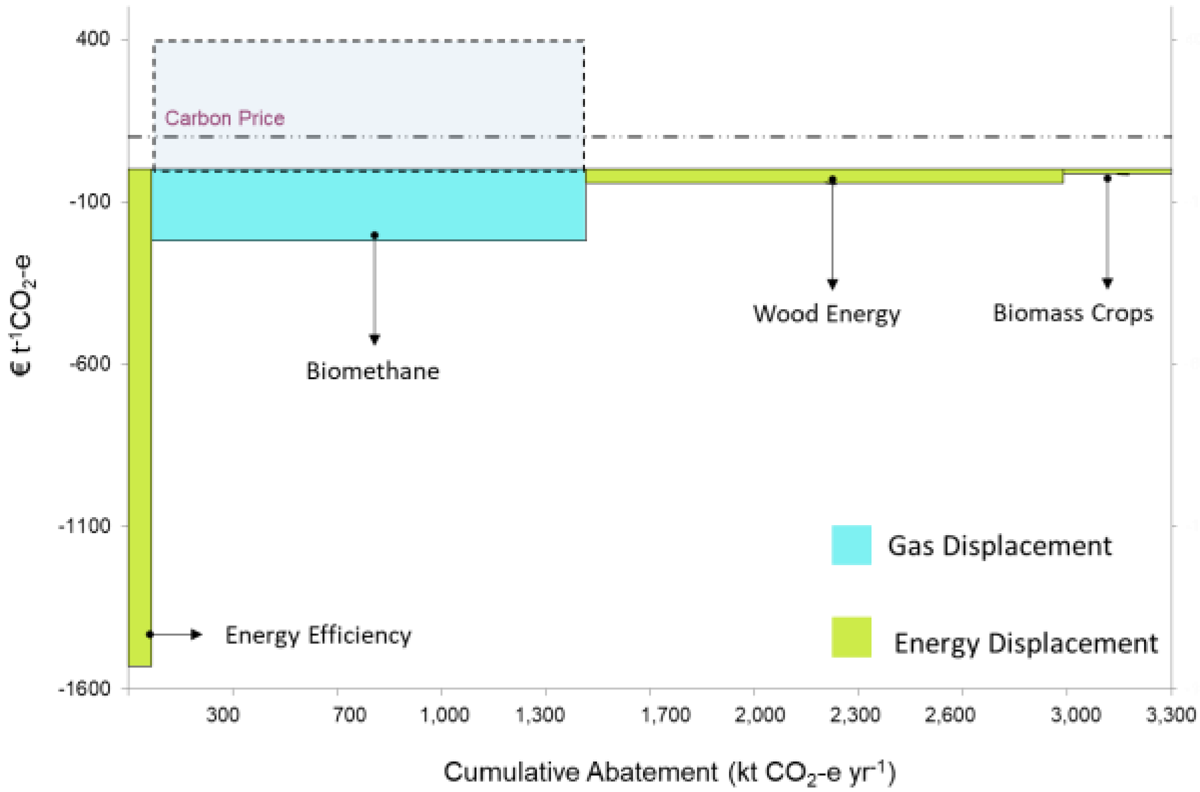


Figure 3.10: *Marginal Abatement Cost Curve for 2030 bioenergy abatement produced in the agriculture and forestry sectors using Pathway 2 uptake levels. Values are based on linear or sigmoidal uptake of measures between 2021 and 2030, and represent the mean yearly abatement over this period. The dashed column indicates the biomethane marginal cost at pre-2022 energy price levels (low cast scenario). Dashed line indicates Carbon cost of €100 per tonne CO_2.*

Total cumulative costs associated with bioenergy measures were highly variable between the low and high cost scenarios, driven mainly by the price of gas and electricity as well as the cost of feedstock (Figure 3.9, 3.10, Table 3.4). The net costs have transformed since the 2018 MACC, where biogas and biomethane costs were estimated at between +€100 $t^{-1}CO_2e$ and +€250 $t^{-1}CO_2e$. Due to unprecedented increases in both fossil fuel and electricity prices due to the Russian invasion of Ukraine, biomethane costs have decreased from +€496 $t^{-1}CO_2e$ under the low cost scenario to between -€198 $t^{-1}CO_2e$ (Pathway 1) to -€219 $t^{-1}CO_2e$ abated (Pathway 2) under the high (current) cost scenario. In addition, the biomethane measure also contributes to two other related measures; the use of digestate in place of N fertiliser and some reduction in livestock (sheep and cattle) numbers.

Total cumulative abatement associated with (bio)energy sector was projected to be between 15.8 $MtCO_2e$ for Pathway 1 and 18.6 $MtCO_2e$ for Pathway 2. The use of wood for energy comprised the bulk of the cumulative abatement, accounting for 84% of total abatement under Pathway 1 with biomethane contributing circa 10%. However, under Pathway 2, the share of biomethane abatement increased to 29% with wood energy accounting for 72%.

Pathway 1 costs ranged from +€50M to -€1105M for Pathway 1 and +€1262M to -€1821M. This wide variation in cumulative abatement costs, particularly for Pathway 2, were principally driven by the variation in net biomethane costs. These were, in turn, driven by the balance between capital expenditure (CAPEX) and operating (OPEX) costs, particularly the cost of grass silage feedstock and the price of energy (gas and electricity), as well as that of bottled CO_2. Under the 'high cost' scenario, the increase in the energy price more than defrayed the increased CAPEX and OPEX costs.

Table 3.4: *Cumulative energy abatement and associated costs for a) two levels of uptake (Uptake Pathways 1 and 2) two levels of costs (Low and High Cost scenario).*

Pathway 1	***Cumulative Mitigation 2021-30***	***Cost Range***		***€M***	***2030 Mitigation***	***2030 Cost***		***€M***
Biomethane	*959*	*€526*	*to*	*-€190*	*266*	*€146.0*	*to*	*-€52.9*
Wood Energy	*13381*	*-€551*	*to*	*-€551*	*1513*	*-€63.2*	*to*	*-€63.2*
Biomass Crops	*1224*	*-€19*	*to*	*-€20*	*339*	*-€5.1*	*to*	*-€5.1*
Energy Efficiency	*295*	*-€1*	*to*	*-€345*	*77*	*-€27.5*	*to*	*-€117.2*
Total	***15858***	***-€45***	***to***	***-€1105***	***2195***	***€50.2***	***to***	***-€238.4***
Pathway 2	***Cumulative Mitigation 2021-30***	***Cost Range***		***€M***	***2030 Mitigation***	***2030 Cost***		***€M***
Biomethane	*3694*	*€1,833*	*to*	*-€875*	*1374*	*€681.9*	*to*	*-€64.8*
Wood Energy	*13381*	*-€551*	*to*	*-€578*	*1513*	*-€63.2*	*to*	*-€54.2*
Biomass Crops	*1224*	*-€19*	*to*	*-€22*	*339*	*-€5.1*	*to*	*-€1.9*
Energy Efficiency	*295*	*-€1*	*to*	*-€346*	*77*	*-€27.5*	*to*	*€4.1*
Total	***18593***	***€1,262***	***to***	***-€1,821***	***3303***	***€586.1***	***to***	***-€116.8***

3.5. Implications for 2030 Targets

3.5.1. Impact of agricultural mitigation on Carbon budgets

The impact of the 'absolute' agricultural GHG reduction measures on the first two carbon budgets (CB's) are shown in Table 3.5.

- Under S1 Business-As-Usual scenario (no mitigation), the FAPRI-Ireland model projects that total sectoral GHG emissions would be 110. $MtCO_2e$ for CB1 and 109 $MtCO_2e$ for CB2. This would be 4.1 $MtCO_2e$ and 12.5 $MtCO_2e$ higher than the assigned emissions ceilings.
- Under Adoption Pathway 1, the sectoral targets were not achieved under any of the activity scenarios (Table 3.5).
- Under Adoption Pathway 2, the sectoral targets were projected to be achieved under Activity Scenarios S1 and S2 and just missed under S3.
- Whilst the level of uptake has been split into two distinct Pathways, a mixture of varying uptake levels could achieve the sectoral ceilings. So, for example, under S2 activity levels, the target would be achieved with a combination of Pathway 1 with Pathway 2 levels substituted for reduced age of finishing and clover/multi-species swards. Similarly, under S1 activity levels, Pathway 2 uptake for reduced age of finishing, fertiliser formulation, diversification, clover/MSS and feed additives

combined with the remainder of measures at Pathway 1 levels of uptake would achieve the targets.

Table 3. 5: *The impact of mitigation on cumulative GHG emissions for the three scenarios and two uptake pathways.*

Uptake Pathway	**Scenario**	**Mt CO_2e**
	Target	202.0
Pathway 1	Scenario 1	206.8
	Scenario 2	203.6
	Scenario 3	210.2
Pathway 2	Scenario 1	198.9
	Scenario 2	196.1
	Scenario 3	203.2

*Agricultural sectoral target (Government of Ireland, 2022)

For sensitivity purposes, total cost-effective measures were defined at three different carbon prices: those measures costed at or below €100, €150 and €250 per tonne CO_2e abated (Table 3.5). The current EU-ETS futures carbon price of 1 tCO_2e is just over €85, while the UK price of allowances is £61, with the UK also having a price floor of £18 per tonne CO_2e. In this MACC analysis for Ireland, under the low cost scenario, the majority of agricultural abatement (78%-86%), LULUCF abatement (81% to 86%) was achievable at a C price of no more than €100 per tonne CO_2e. However, there was a wider range for energy, with 58% -88% achievable by 2030. This was due to the large proportion of biomethane occurring under Pathway 2, which was priced at over €400 $t^{-1}CO_2e$ under a *low cost* scenario. However, at the higher cost scenario, 100% of bioenergy measures were implementable for under €100 $t^{-1}CO_2e$. In contrast, only between 49% - 52% of LULUCF was implementable at that price and 62% to 69% of agricultural abatement. At €150 $t^{-1}CO_2e$, 64%-87% of agriculture and LULUCF measures were implementable, with the proportion rising to >90% at €250 t-1CO_2e (Table 3.6).

Table 3. 6: Table of the percentage abatement achievable for a €100, €150 and €250 carbon price.

Uptake Pathway	**Sector**	**Carbon price Low Cost Scenario**			**Carbon price High Cost Scenario**			**Total 2030 Abatement**
		€100	€150	€250	€100	€150	€250	kt CO_2e yr^{-1}
Pathway 1	Agriculture	78%	78%	83%	62%	64%	90%	2807
	LULUCF	81%	81%	97%	53%	81%	97%	2273
	Energy	88%	88%	88%	100%	100%	100%	2195
Pathway 2	Agriculture	86%	91%	98%	69%	86%	98%	5229
	LULUCF	87%	90%	97%	49%	87%	94%	4260
	Energy	58%	58%	58%	100%	100%	100%	3303

The impact of LULUCF mitigation on Carbon budgets Mitigation from land-use/land-use change and forestry (LULUCF) is projected to deliver cumulative abatement of between 12,772 ktCO_2e and 21,569 ktCO_2e over the period 2021-2030. There are no sectoral emissions ceilings for LULUCF to date, pending the outcome of ongoing the Land-Use Review. However, the proposed EU LULUCF Regulations do have a target for Ireland. This target was set at 3,740 ktCO_2 assuming a 2016-18 baseline of 4,330 ktCO_2. As actual 2016-28 LULUCF emissions were 7,271 ktCO_2 the amended target would then be 6,680 ktCO_2 (Table 3.7). Assuming BAU sectoral emissions of 46,099 and 52,167 ktCO_2 for CB1 and CB2 respectively, Pathway 1 would deliver CB1 and CB2 emissions 12.3% and 21.0% below BAU emissions, but importantly emissions would be 13.7% above the EU baseline (2016-2018 emissions) and 20.6% above 2018 emissions. Pathway 2 mitigation would mean that sectoral emissions would be 13.7% below 7,271 ktCO_2e EU baseline and thus would meet the target set under the LULUCF Regulations. However, emissions would only be 8% below 2018 emissions. However, the Climate Action Plan 2021 proposed a sectoral reduction band for LULUCF of between 37% and 58% below 2018 values. In order to achieve these targets, deep inventory refinement allied to an afforestation campaign would be required, including a refinement of the area and drainage status of peat soils, the land-use factors and land management factors associated with mineral and peat grassland and also croplands.

*Table 3. 7**:** Annual mitigation associated with LULUCF measures (both pathways), EU LULUCF targets (recalculated to account for new EF from afforested peat soils) and cumulative emissions for Carbon Budgets 1 and 2 under BAU, moderate and enhanced pathways.*

Annual Emissions/Abatement		***2018***	***2025***	***2030***
BAU	*ktCO_2e yr^{-1}*	*7271*	*9926*	*10537*
Mitigation (Pathway 1)	*ktCO_2e yr^{-1}*		*1224*	*2202*
Mitigation (Pathway 2)	*ktCO_2e yr^{-1}*		*2077*	*4118*
Total Emissions (Pathway 1)	*ktCO_2e yr^{-1}*		*8702*	*8335*
Total Emissions (Pathway 2)	*ktCO_2e yr^{-1}*		*7849*	*6419*
*EU Reg. Target trajectory**	*ktCO_2e yr^{-1}*		*6890*	*6682*
Cumulative Emissions/Abatement				
BAU	*ktCO_2e*		*46099*	*52167*
Cumulative Mitigation (Pathway 1)	*ktCO_2e*		*2604*	*10168*
Cumulative Mitigation (Pathway 2)	*ktCO_2e*		*4471*	*17098*
Total Emissions (Pathway 1)	*ktCO_2e*		*43495*	*41999*
Total Emissions (Pathway 2)	*ktCO_2e*		*41628*	*35069*
*EU Reg. Target trajectory**	*ktCO_2e*		*34873*	*33822*

*Original LULUCF target for Ireland of 3.74 MtCO_2e by 2030 is revised to 6.68 due to the impact of drainage on afforested organic soils, which are increasing from 0.59 tC ha^{-1} yr^{-1} to 1.68 tC ha^{-1} yr^{-1} (Jovani-Sancho et al. 2021). ** Baseline for EU LULUCF Regulation

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.

3.5.2. Impact of bioenergy measures on energy sector emissions

Bioenergy has the potential to displace cumulative fossil fuel emissions of 15858 $ktCO_2e$ (Pathway) 1 and 18593 $ktCO_2e$ (Pathway 2) during the 2021 to 2030 period with the majority of the abatement coming during the second carbon budget (Table 3.8). This means that across the five main energy sectors (power generation, manufacturing combustion, residential, commercial and transport), agricultural-sourced bioenergy and energy saving could contribute between 23% (Pathway 1) and 27% (Pathway 2) of the required energy sector emissions reduction.

Table 3. 8: Annual projected GHG emissions ($ktCO_2e\ yr^{-1}$) from energy sub-sectors in 2025 and 2030, the mitigation associated with bioenergy and energy saving measures (both moderate and enhanced pathways) and cumulative emissions and abatement for Carbon Budgets 1 and 2 under BAU, moderate and enhanced pathways.

Annual Emissions/Abatement	**Unit**	**2018**	**2025**	**2030**
Total Energy	$ktCO_2e\ yr^{-1}$	38500	33083	25894
Target	$ktCO_2e\ yr^{-1}$		25250	18000
Pathway 1	$ktCO_2e\ yr^{-1}$		1600	2195
Pathway 2	$ktCO_2e\ yr^{-1}$		1587	3303
Energy P2	$ktCO_2e\ yr^{-1}$		31483	23699
Energy P1	$ktCO_2e\ yr^{-1}$		31496	22591
Cumulative Emissions/Abatement				
BAU			172778	140876
Sectoral Target	$ktCO_2e$		140750	104500
Cumulative Mitigation (Pathway 1)	$ktCO_2e$		6241	9618
Cumulative Mitigation (Pathway 2)	$ktCO_2e$		6246	12347
Total Emissions (Pathway 1)	$ktCO_2e$		166538	131259
Total Emissions (Pathway 2)	$ktCO_2e$		166532	128529

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3.6. Exchequer Costs

The estimation of exchequer costs for the 2021 to 2030 period was performed using current or proposed grant-aid schemes. Where grant aid does not occur and was assumed to be unlikely to arise, no costings were attributed. Individual exchequer costs are detailed in Section 4. Total cumulative costs to 2030 were estimated at between €1,428m and €3,208m.

Table 3. 9: *Projected cumulative costs 2020 to 2030 associated with MACC measures. Italics indicate measures currently not funded but where there is equivalent funding available (eg. TAMS)*

Measure	Pathway 1	Pathway 2
	€ million	€ million
Beef Measures	€260	€260
TAMS measures (LESS & aeration)	€27	€55
Clover	€37	€144
Liming	€8	€8
Forestry	€443	€863
Peatlands	€1	€1
Hedgerows	€109.40	€218.80
Crop measures	€16	€26
Bioenergy	€442	€1,500
Diversification	€47	€94
Energy Saving	€31	€31
Biomass	€7	€7
Total	€1,428	€3,208

3.7. Trade-Offs and Synergies with other Environmental Legislation

Aside from GHG emissions ceilings, there is also a requirement to reduce ammonia emissions in the context of both the National Clean Air Strategy and the National Emissions Ceiling Directive (NECD). Ireland breached its ammonia emission ceiling for the period up to 2020 and remains in breach of NECD targets. In addition, ammonia is a principal loss pathway for agricultural nitrogen and the reduction of these emissions should be a key focus for improving farm efficiency and sustainability. This is particularly relevant in the context of the Food Vision 2030 Strategy. An ammonia MACC analysis (Buckley et al. 2020) has also been conducted, and is relevant to this analysis as ammonia indirectly contributes to N_2O production and because also individual ammonia mitigation and GHG mitigation measures can be either complementary or antagonistic.

The analysis revealed that there was a potential ammonia mitigation of 22 kt NH_3 yr^{-1} by 2030, which would cost €79M per annum. Importantly, the bulk of the abatement was to be achieved via the use of protected urea fertiliser (coated with a urease inhibitor NBPT) and the adoption of low emission slurry spreading. While LESS was expensive in terms of GHG mitigation (between €183 $t^{-1}CO_2e$ and €364 $t^{-1}CO_2e$), the measures cost in terms of ammonia abatement was estimated to be relatively low (circa €4 per kg NH_3). Aeration, on the other hand, reduces methane by over 40% but can increase ammonia emissions by over 20% (Amon et al. 2006, Calvet et al. 2017).

Most of the N-abatement measures analysed in this study have either a positive or, at worst, little impact on water quality. In particular, reduced crude protein, that reduces N excretion and measures that reduce mineral N requirement were win-win from a water quality as well as GHG perspective. Similarly, fertiliser formulation, which maintains N in the ammonium form, should reduce N leaching (Forrestal et al. 2016, 2017). GHG mitigation measures, which are antagonistic in term of their impact on water quality, included extended grazing and drainage of mineral soils. Extended grazing, while reducing GHG and ammonia 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 were used in the suite of measures to increase efficiency. Other measures, such as increased broadleaf forestry, improved hedgerow management and the restoration of peatland should also significantly enhance biodiversity, while low-emission slurry spreading will help preserve heathland and bog habitats via reduced N deposition into N sensitive habitats.

4. Diversification & Future Measures

4.1. Organic Farming

The national policy position regarding an expansion of organic farming was outlined in Section 1.3.4. This ambition reflects a key aim of the EU 'Farm to Fork Strategy' (European Union, 2020), which looks to enshrine the principles of sustainability within the new CAP, emphasising input reduction and promotion of organic farming systems. More broadly, the European Green Deal and the Farm to Fork and Biodiversity strategies, have, in addition to a specific objective to increase organic farming, also set out targets for reducing nutrient losses and the use of fertilisers, pesticides and antimicrobials. Increasing the proportion of land farmed organically, is seen as key to achieving these latter targets.

The Government target of 7.5% of agricultural land in organic farming by 2027 is less than the current EU average of 9.1% but should be considered in the context of the current 2% and the historically low conversion rates to organic farming. Nonetheless, the enhanced payment rates for participation in the Organic Farming Scheme and the consequent large number of applicants gives rise to an expectation that land area in organic farming will increase considerable in the forthcoming years.

The largest organic sector in Ireland is beef cattle production. According to DAFM, there were almost 3,000 organic farms in Ireland in 2020 with approximately half of these being cattle farms and a further 20% sheep farms. Horticulture/cereals account for a further 20% with a smaller number being poultry farms (~7%). The number of organic dairy farms in Ireland is low (approximately 60 farms representing less than 2% of all organic farms. Given these numbers, the expectation is that the greatest rate of conversion to organic farming systems will be on cattle farms.

The implications for national GHG emissions of an increase in land area in organic farming will largely be mediated through: reduced use of inorganic fertilizers, particularly N; lower stocking rates on livestock farms and thus fewer livestock nationally; and change in finishing age of beef cattle relative to conventionally farmed beef cattle. These effects have been considered in the individual measures included in the MACC. Reduced N due to an increase in organic farming is incorporated in the assumed reduction in inorganic N fertilizer derived from the 'Liming' and 'Clover & MSS' measures. The implications of an increase in organic farming on the national bovine population are likely to fall within the range of the base case population scenario (S1) and the low population scenario (S2).

Typically age at finishing for beef cattle on organic farms is older than for conventional farms. In the present analysis, it was assumed that across the bovine population finishing age reduces from 25.2 months in 2021 to 23.0 months and 22.0 months for Pathways 1 and 2, respectively. This may be offset to some extent by an increase in beef cattle produced on organic farms; however, given that organic beef farms will tend to be lower stocked than conventional farms, the overall impact on the national population is expected to be relatively modest.

Other diversification measures such as forestry and production of feedstock (grass silage) for anaerobic digestion are dealth with above and in the appendices).

4.2. Future Measures

Future measures, include 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.

Circularity within the agri-food sector has much un-tapped potential. 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 processing of digestates arising from biomethane production into higher value bio-based fertilisers is already occurring in jurisdictions where they are widespread, from simple solid/liquid separation to more complex processing (Atieno et al. 2020, Mitter et al. 2021). Nonthermal plasma (NTP) can dissociate atmospheric N molecules and directly fix them into liquids. This allows for the production of both oxidized and reduced forms of nitrogen and produces far less GHG compared to the Haber-Bosch process (Ranieri et al. 2020). Currently, the use of NTP for enhancing the mineral N content of animal manures is commercially available, but the full GHG emissions associated with these 'enhanced manure' products has yet to be quantified.

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. The use of biochar may, in fact, offer a way to permanently and verifiably sequester carbon whilst also acting as a soil conditioner that helps make available more soil nutrients, particularly soil P, as the biochar has been denosntrated to act as sites for mycorrhizal colonisation (Li et al. 2019).

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. Breeding for low methane bovines is currently being researched by ICBF and Teagasc.

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 (Vitousek et al. 2013, Soumare et al. 2020). The development of new nitrification inhibitors and inclusion of current ones into the market, assuming inclusion of a residue standard into the Codex Alimentarius, would also substantially reduce N_2O emissions.

5. Knowledge Transfer

The amount of GHG emissions reduction achieved through the adoption of the identified mitigation measures is dependent on both the rate and extent of adoption of the various measures by farmers. Sectoral emissions reduction will be the result of farmers' willingness to make adjustments on their farms (Farstad *et al.*, 2021) and the decisions and actions of individual farmers. Farmers, and those working with and supporting them in the Irish Agricultural Knowledge and Innovation System (AKIS), will evaluate the mitigation measures through many filters, requiring translation and tailoring of the research findings to different needs (Sewell *et al.*, 2017). Consequently, the ongoing delivery of knowledge transfer/ innovation support services to farmers is critical to supporting practice adoption at farm-level that will impact on reducing greenhouse gas emissions.

In a recently published review of extension methods (Nettle *et al*., 2022), nine different mechanisms that can encourage learning and change were identified, including: group-learning/peer-to peer; technology development; training; information provision; one-on-one advice/coaching; e-extension; co-innovation; best management practice; and social marketing. The nine methods were found to have different strengths and weaknesses in supporting change as well as attributes that influenced the quality and impact of their implementation. The authors presented a framework for considering the relative strengths of each extension method according to different change contexts (distinguished by the level of complexity and uncertainty involved in that change). The table is reproduced below. This framework can assist policy makers, scientists, advisory services and farmers in identifying the most appropriate method, or combination of methods, to develop effective and impactful extension strategies. A key finding from the review (Nettle *et al*., 2022) was that rather than "anything will do", a considered approach to the selection of methods is required. Furthermore, the strongest evidence for the effectiveness of methods in the extent, reach and time to change was toward small-group learning and provision of direct advisory or coaching services. However, including and integrating a combination of methods, with a focus on addressing farmer needs and supporting a journey of change, were key to a greater impact. Providing information alone proved weakest. Finally, the review called for investment in research programmes, and in research designs and methods that incorporated the social dimensions of adoption.

Table 5. 1: A framework for assessing the relative strength of extension methods (1 to 9) according to the attributes of the context for change (A, B or C), derived from the review and case study findings.

Context for change (A – C)	A	B	C
Extension methods (1 – 9)	The farm-practice context and impact from change is known and uncontested	The farm-practice context and impacts from change are known, yet there are complexities and uncertainties in implementing change	There is complexity, uncertainty or long time-frames in changing farm practices or in knowing the impacts from change
1. Facilitated groups/ peer learning	Moderate	Strong	Strong
2. Technology development	Moderate	Strong	Strong
3. Training	Strong	Moderate	Weak
4. Information provision and access	Strong	Moderate	Moderate
5. One-on-one/ consultancy (coach)	Strong	Strong	Weak
6. E-extension	Strong	Moderate	Weak
7. Co-innovation	Weak	Moderate	Strong
8. Best management practice	Strong	Moderate	Weak
9. Social marketing	Strong	Moderate	Weak

The primary focus of each of the nine extension methods:

1. Facilitated groups/peer learning: provides a platform for social learning and can include focus farms and demonstrations.
2. Technology development: collaborative approaches with farmers to address specific topics and problems such as application of a new technology or tools.
3. Training: enables the development of knowledge, skills and techniques as a foundation for change.
4. Information provision and access: facilitates access to relevant information.
5. One-on-one/ consultancy (coach): provides individual support to make decisions about changes.
6. E-extension: uses information and communication technologies to provide information and extension support virtually/remotely.

7. Co-innovation: collaborative process that brings people together to negotiate and implement shared goals and outcomes.
8. Best management practice: a formalised process for self-assessing capacity and then responding to gaps or deficiencies.
9. Social marketing: aims to better understand and engage people to towards specific behaviour changes.

From the farmer's perspective, it is worth considering the key drivers of change, as well as the critical enabling conditions that facilitate such change. A recent study (Farstad *et al*., 2022) identified that climate mitigation measures are appreciated for offering farm beneficial functions other than climate change mitigation. Farmers take a pragmatic approach to farming, adopting relevant technologies and practices as a means of improving their farm management, with climate benefits seen as a "positive side effect, but not centre stage". While undoubtedly this is a challenge in terms of the adoption of mitigation measures, the authors conclude that this provides an opportunity for practice change even if farmers are not particularly climate oriented (through focussing on the economic co-benefits of the particular measure). The same study found that weak climate consciousness is not an important barrier to farmers' mitigation actions. These findings suggest the need for careful and considered message framing when promoting mitigation technologies to farmers. In the same study, the authors also highlight the requirement both to tailor critical enabling conditions for farmers and to deliver targeted programmes and campaigns emphasising the farm related benefits of mitigation technologies. The critical enabling conditions are described as shared, favourable, contextual conditions enabling the implementation of climate mitigation measures on individual farms, and those identified in the Farstad *et al*., (2022) study include: a profitable farming operation, scale of operation, sufficient time for farming, an identified successor and relevant subsidy schemes. While these measures can enable implementation, in their absence (or poor design), it can limit the ability of farmers to act in climate beneficial ways. When enabling conditions are absent, neither climate consciousness (on the part of the farmer) nor interests in other benefits (from the technology) will be enough to stimulate change. Finally, the authors highlight the mutual dependency of enabling conditions, farmer motivations and message-framing and identify the need for both research and development strategies that consider all parts.

Signpost Farm and Advisory Programme

A targeted programme is the Teagasc-led, whole of industry Signpost Programme, www.teagasc.ie/signpost. Launched since the publication of the previous MACC in 2018, this major knowledge transfer initiative aims to lead climate action by all Irish farmers. The purpose of the Programme is to lead and support the transition of Irish farming towards more sustainable farming systems, with a specific objective to reduce agricultural emissions in line with national policy objectives. There are three parts to the overall programme:

1. Signpost Farms: a network of over 120 demonstration farmers who can be amongst the first to adopt climate mitigation technologies, and can share their experiences with other farmers through a range of farmer-to-farmer activities and media channels;
2. Signpost Advisory Programme: a new, free-of-charge, targeted advisory service, which will be available to all farmers, and will provide enhanced advisory and training support to farmers to enable them to identify, select and implement climate and sustainability actions suitable for their farms; and
3. National Agricultural Soil Carbon Observatory (NASCO): a long-term research trial, established in 2021, with the aim of providing accurate, long-term information on the carbon dynamics of Irish agricultural systems, including the provision of improved measurement, modelling and mapping of carbon uptake and release from agricultural land and accurate assessment of carbon sequestration.

In addition, Teagasc, Bord Bia and ICBF, with the support of the Department of Agriculture, Food and the Marine, are developing a digital platform ("AgNav"), to provide a science led, decision support and planning tool with specific, accurate and verifiable data to famers to enable climate action. This will be a key enabling tool for advisors in the delivery of the Signpost Advisory Programme. The AgNav platform will allow farmers to quantify their farm's gaseous emissions (both GHG and ammonia, referred to as "Know My Number") while then facilitating the creation of a farm specific, action list (referred to as "Make My Plan"). The digital platform will provide individual farmers with farm specific indicators of their current status (baseline or starting point) as well as over time their future performance, both in terms of their overall gaseous emissions, but also in terms of progress made in the uptake of mitigation measures and reductions in emissions.

6. Summary and Recommendations

6.1. Agriculture

Achieving the sectoral targets associated with the Climate Action & Low Carbon Development Act will be extremely challenging for the agriculture, forestry and land-use (AFOLU) sectors. The level of potential mitigation was estimated to range from 2,820 ktCO_2e yr^{-1} for Pathway 1 uptake to 4,857 ktCO_2e yr^{-1} for Pathway 2 uptake.

Under Uptake Pathway 1, only the S2 activity scenario approaches the 17.25Mt CO_2e yr^{-1} target. Under Pathway 2 levels of uptake, mitigation of methane and N_2O achieves the target of reducing emissions to 17.25 MtCO_2e (or 17,250 kt CO_2e) under both S1 and S2 activity scenarios and almost achieves the target even under S3 activity levels. Under S2 activity levels, the target is estimated to be over-achieved by 1.25 Mt CO_2e. In fact, S2 activity levels would achieve the target with high (Pathway 2) levels of reduced finishing age, feed additives and fertiliser formulation and Pathway 1 levels of uptake for the remainder of measures. Therefore, the two Pathways should not be seen as mutually exclusive and a 'mix and match' approach in terms of differential levels of uptake of measures could achieve the targets.

Agricultural abatement looks, on paper, very cheap and indeed is cost-negative. However, the bulk of the cost savings are associated with two measures: Dairy EBI and reduced age of finishing. If these two measures are excluded from the total, cumulative costs would range from €256M to €730M over the budgetary period with maximum annual costs in 2030 ranging from €93M to €199M.

It should be stated that the very high abatement levels required in Pathway 2 will be extremely challenging to achieve over the next seven years. Many of the uptake rates demanded in Pathway 2 (e.g. 95% replacement of CAN and 100% replacement of straight urea), would almost certainly require policy intervention in tandem with incentivisation schemes.

Table 6. 1: Baseline emissions in 2018 & 2030, 2030 emissions after implementation of mitigation measures , cumulative mitigation over the 2021 to 2030 period, 2030 cost range and cumulative costs over the 2021 to 2030 period for Agriculture (S1, S2 S3) , LULUCF and Energy.

			GHG emissions MTCO2e/yr		Emissons in 2030	**Cumulative emission reduction**	*Cost Range €M*					
Scenario	**Pathway**	**Sector**	**BAU 2018**	**BAU 2030**	**2030**	**MTCO2e 2021-30**	**2030 Cost**			**cumulative Cost 2021-30**		
1	1	Agriculture	23	21.9	19.1	13.1	-€422	to	-€219	-€2,253	to	-€1,223
2	1	Agriculture	23	21.1	18.3	12.7	-€407	to	-€203	-€2,179	to	-€1,281
3	1	Agriculture	23	22.8	19.9	13.5	-€435	to	-€212	-€2,323	to	-€1,151
1	2	Agriculture	23		17.1	21.04	-€363	to	-€294	-€2,017	to	-€1,685
2	2	Agriculture	23		16.4	20.16	-€355	to	-€279	-€1,945	to	-€1,748
3	2	Agriculture	23		17.8	21.69	-€376	to	-€285	-€2,084	to	-€1,598
-	1	LULUCF	6.85	10.5	8.35	12.8	€170	to	-€111	€305	to	€147
-	2	LULUCF	6.85		6.42	21.6	€259	to	€284	€279	to	€280
-	1	Bioenergy	38.5	25.9	23.7	15.8	€50.20	to	-€238	-€45	to	-€1,105
-	2	Bioenergy	38.5		22.6	18.6	€586	to	-€117	€1,262	to	-€1,821

6.2. Land use, Land-use Change and Forestry and Energy Mitigation

LULUCF mitigation potential was estimated to be between 2,202 ktCO_2e yr^{-1} and 4,118 ktCO_2e yr^{-1} by 2030. Cumulative emissions savings would be between 12,772 ktCO_2e to 21,569 ktCO_2e across both carbon budgets. The associated costs were projected to range from -€111m to +€284M and these depended of the relative balance between the level of uptake between costs saving measures, such as extended rotation and cost-positive measures such as hedgerow and forest planting (Table 6.1). While Pathway 2 levels of mitigation would be sufficient to reach proposed EU LULUCF targets, these reductions would come nowhere near the 37% -58% reduction as proposed under the Climate Action Plan 2021, due to the increase in underlying LULUCF emissions projected to occur up to 2030. An additional reduction of 2,195 – 3,033 ktCO_2-e can be contributed via fossil fuel displacement via energy saving and the use of bio-energy at a net cost of between +€1,399m and -€1,849m per annum. Over the 2021-2030 period, bioenergy supported with AFOLU feedstock could comprise 6.5% to 7.5% of energy mitigation across the entire budgetary period and by 2030 could account for circa. 20% of annual fossil fuel displacement. However, none of this abatement accrues to the agricultural sector (unless it displaces green diesel). As the contribution of AFOLU to the wider bioeconomy is projected to grow significantly over the next two decades, these are issues that must be addressed to deliver an equitable solution for both the energy and AFOLU sectors.

Further reductions to 2050 will require an investment in research to develop breakthrough mitigation options combined with an integrated knowledge transfer strategy strategies and the development of policies that will incentivise adoption or a fundamental change in Irish agriculture. In particular, the capacity of LULUCF to decrease emissions will be severely disadvantaged without a) more refined activity date and b) higher Tier emission /land-use or land management factors that accurately describe national land-use and improvement/deficits in land management.

6.3. Recommendations:

Methane:

- A number of feed additives have been proven effective (3-NOP and RumenGlas) in Ireland through the Meth-Abate and VistaMilk projects in indoor confined systems. Further research is required on the re-formulation (e.g. slow release and bolus technology) of these feed additives for application in beef and dairy grazing systems. There is a major requirement to ensure any successful feed additives have full EU EFSA approval prior to national delivery on farms. In order to fast track this process for new products such as RumenGlas, funding for the completion of EFSA specific feeding trials in Ireland to prove safety as well as efficacy is urgently required.

- Ireland is leading the way by publishing the first enteric methane across breed genetic evaluations on AI sires. The generation of Methane Evaluations comes as a direct result of the collaborative effort between ICBF, DAFM and Teagasc through innovative projects such as GREENBREED, RumenPredict and MASTER and the Irish Research

Council. These proofs need to be tested and validated across diets and particularly in grazing systems.

- As a country, Ireland has been slow in performing methane measurements on different animal types and ages across various feeding systems due to a lack of equipment until recently. In order to refine our national GHG inventories on methane, further staff and methane measurement equipment is urgently required to perform these measurements in both cattle and sheep. Currently there is a severe shortage of methane measurement equipment for sheep (there are no GreenFeed systems for methane measurement in sheep in the republic of Ireland with PAC measurement not recognised by IPCC). There is a national requirement to move from Tier 1 to Tier 2 for methane counting in sheep, however more baseline country specific methane data is required to achieve this.
- 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 adoption of best available technologies (particularly low cost measures) that have been identified.

Nitrous Oxide

- Reduce N fertiliser usage and optimise soil nutrient status as well as promoting low N_2O fertilisers and bio-based fertilisers.
- 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.
- The development of biofertilisers and new mineral fertilisers with urease and nitrification inhibitors should be prioritised.

Land-Use and energy

- Further research into forestry management, agroforestry and hedgerow management, particularly the inclusion of new species into hedgerows to maximise C sequestration and biodiversity.
- The development of a national biomethane policy to encourage the adoption of grass and other biomass-fed anaerobic digestion 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.

Other Issues

- 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.

- Targeted knowledge transfer initiatives (including the development and leverage of the Signpost Programme through both the Demonstration Farm and Advisory components), to maximise farmer support to facilitate maximum adoption of technologies and practices. These initiatives should include maximum reach and integration across the entire AKIS, as well as providing scope for co-creation and innovation and tailored solutions through all available knowledge transfer and knowledge exchange channels.
- To consider
    - Reducing emissions from peat soils – inventory refinements, water management, paludiculture
    - Carbon farming
    - Diversification options such as alternative proteins
    - Climate adaptation – impact of climate change on carbon and nitrogen losses from soil such as C Sequestration.

7. Individual Measures

7.1. Agriculture Measures

1. Dairy EBI: Both an efficiency and absolute emission reduction measure

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e by 2030
Efficiency Reduction	261	842	390	-244.5	-426	-618
Absolute GHG Reduction	142.5	255	156.0	-244.5	-426	-1776
Range	142.5 to 261	255 to 842	17.9 to 156			-667 to -1776

See A1.1 for full assumptions and results

The Economic Breeding Index (EBI) was introduced in Ireland in 2001 to identify genetically superior animals in order to increase profitability among Irish dairy herds (Veerkamp et al. 2002). This single-figure profit index is designed to assist farmers in identifying the most profitable bulls and cows for breeding dairy herd replacements. Among the subindices are milk production, fertility (calving interval and survival), calving performance, beef carcass, cow maintenance, cow management, health, and more recent carbon (Berry et al. 2007, O'Brien et al. 2011). The EBI favours animals whose progeny have a long herd life, produce a large quantity of high composition milk annually within a 365-day calving interval, are easy calving and have progeny who will calve easily in the future, while also accounting for beef merit of progeny.

Emissions Reduction Assumptions

The abatement measure "improving genetic merit of the dairy herd" is based O'Brien et al. (2011) and Lahart et al. (2021). O'Brien et al. (2011) calculated GHG emissions from three strains of Holstein-Friesian cows differing in genetic merit whereas Lahart et al. (2021) calculated GHG emissions from two strains of EBI; national average and high genetic merit (top 5%). The results of these field studies were included in the Moorepark Dairy System Model (Shalloo et al., 2004) and the Teagasc dairy life cycle assessment model (O'Brien et al. 2011) to calculate economic performance and GHG emissions of cattle of divergent genetic merit.

Impact on GHG footprint

O'Brien et al. (2011) and Lahart et al. (2021) reported that increasing genetic merit via EBI reduced GHG emissions per unit of product by 2% and 1%for every 10 euro increase in EBI, respectively. 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. Increasing EBI reduces emissions through a) Improving fertility, which reduces calving intervals and replacement rates; b) Increasing milk yield per unit of grazed grass, and improving milk composition which reduces GHG emissions per unit of product. This increases the efficiency of production, which decreases emissions (Martin et al., 2010). Mitigation of the dairy footprint 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.

In order to calculate the impact on total milk solid production, the number of cows required to reach the total milk solid output of the increased EBI herd was calculated and the difference in emissions or 'emissions avoided' was calculated. By 2030, it was calculated that 1,691,000 dairy cows at an EBI of €240 per head would produce 862 kt MS yr-1. This would require 1,769,000 dairy cows at an EBI of €160 per head, resulting in an extra 639kt CO_2e yr^{-1} by 2030.

Impact on absolute methane emissions

Recent data from field trials have shown that methane emissions from higher EBI bovines are lower than lower EBI animals for the same daily gross energy intake. For every €10 increase in EBI, there was a 0.32% decrease in methane emissions (Lahart et al. 2022). Therefore, assuming a projected increase in EBI to €240 per head, methane emissions per head would be 125.2 $kgCH_4$ hd^{-1} compared to 130.5 $kgCH_4$ hd^{-1} in the absence of any EBI increase. This equates to a 255 $ktCO_2$e yr^{-1} decrease in methane emissions.

Uptake Assumptions

The scenario analysed assumed that dairy EBI would increase to €240 per cow, with an increase in milk delivered per farm will increase to circa 590,000 litres, at almost 3.6% protein and 4.45% butterfat.

Cost Assumptions

The net economic benefit for EBI was assumed to be €2 per euro increase in EBI (O'Brien et al. 2011, O'Sullivan et al. 2020).

Barriers to uptake

There has historically been few barriers to EBI uptake. The average EBI per cow calving increased from −€28 in 2000 to €151 in 2021 or resulted in an increase of €8.5 per year (ICBF, 2021).

2. Beef Genetics

2.1. Improved Replacement Index: Efficiency measure only

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Efficency Pathway 1	13.3	27.3	14.34	-2.3335	-1.912	-741
Pathway 2	22.1	45.6	23.91	-3.889	-3.187	-741
Range	13.3 to 22.1	27.3 to 45.6	14.34 to 23.91	-2.33 to -3.89	-1.91 to -3.19	-741

See A1.2 for full assumptions and results

The impact of a range of index traits on system gross GHG (kg CO2e / breeding cow / year / trait unit) and system GHG intensity (kg CO2e / kg meat carcass/ breeding cow / year / trait unit) has been modelled (Quinton et al. 2018). This included the impact of trait alteration on reducing feed consumption and associated emissions/costs associated with feed production, and methane production on per animal and per unit meat production basis. Trait responses to index selection were predicted from linear regression for each index trait on their Replacement Index value. Regression coefficients were used to calculate responses in terms of both absolute greenhouse gas emissions and emissions intensity to index selection. The Replacement Index (RI) was predicted to reduce system gross GHG emissions by 0.81 kg CO2e breeding cow-1 year-1 €-1 index , and system GHG emissions intensity by 0.0089 kg CO2e kg-1 meat breeding cow-1 year-1 €-1 index (Quinton et al. 2018). Reductions were mainly driven by improved health and survival, reduced mature cow maintenance feed requirements and shorter calving interval.

Emissions, uptake and cost assumptions

This analysis assumed a 65% adoption of the Suckler Cow Efficiency Programme (SCEP), with a national increase in the RI of €3 per year and a reduction in system EI of 0.009 kg CO2e/kg meat per breeding cow per year per € RI. This is projected to yield total cumulative cost benefits of €23 19 million by 2030 when compared to 2021. For Pathway 2, the increase in RI RI value per year is increased to €5 and consequently GHG emissions savings are increased and cumulative cost benefits increase to €38 38 million. 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.

Sensitivity Analysis

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 and the rate of uptake.

Improved Terminal Index: Agricultural efficiency measure

Pathway	Abatement in 2025 ($ktCO_2e$ yr^{-1})	Abatement in 2030 ($ktCO_2e$ yr^{-1})	Mean abatement ($ktCO_2e$ yr^{-1})	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Efficency Pathway 1	0.2	0.5	0.27	-1.956	-1.808	-33519.6
Pathway 2	0.5	1.1	0.62	-4.093	-3.762	-33519.6
Range	0.2 to 20.5	0.5 to 1.1	0.27 to 0.62	-1.96 to -4.09	-1.81 to -3.76	-33519.6

See A1.2 for full assumptions and results

The impact of beef genetics on terminal traits has been quantified with reductions in system emissions intensity of 0.018 kg CO_2e $head^{-1}$ $year^{-1}$ $€^{-1}$ index (Quinton et al. 2018), driven by increased meat production from improvements in carcass weight, conformation and fat. The approach followed mirrored that applied for the Replacement Index; thus the impact of trait alteration on reducing feed consumption and associated emissions/costs associated with feed production, and methane production on per animal basis were quantified. Trait responses to index selection were predicted from linear regression for each index trait on their Terminal Index value. Regression coefficients were used to calculate responses in terms of absolute greenhouse gas emissions to index selection.

Emissions, uptake and cost assumptions

This analysis assumed a continuation of current genetic trends in for Pathway 1 with a national increase in the TI of €2.30 per year. This is projected to yield total cumulative cost benefits of €23 million by 2030 when compared to 2021. For Pathway 2, the increase in RI value per year is increased to €5 and consequently GHG emissions savings are increased and cumulative cost benefits increase to €38 million. 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.

Sensitivity analysis

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.

Beef Index Considerations

Inventory inclusion

As these are efficiency measures, the GHG reduction impact is calculated as the reduction in animal numbers required to maintain the Business-As-Usual production output of meat.

Barriers to uptake

Unlike dairy EBI, beef genetics cut across a range of breeds and crossbreeds. As a result, deconvoluting the impact of genetic merit is more difficult compared to breeding in the dairy industry. In addition, a large cohort of livestock farmers are part-time and have much lower margins compared to their dairy counterparts (Buckley et al. 2022). The BDGP scheme has given an initial kick-start to the improvement of beef genomics and, while its impact on reducing C footprints and total GHG emissions is yet to be quantified, the analysis of Quinton et al. (2018) and the known impact of progress in individual traits (e.g. Taylor et al., 2020) provides confidence of potential of beef breeding to reduce GHG emissions.

Exchequer Costs

The Suckler Carbon Efficiency Programme has allocated €260M across a five year period (2023-2028)

3. Animal Health: Efficiency measure only

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Moderate	205.5	411	226	-1.641	-3.283	-7.99
Enhanced	411	822	452	-3.283	-6.566	-7.99
Range	205 to 411	411 to 822	226 to 452	-1.64 to -3.28	-3.28 to -6.57	-7.99

See A1.3 for full assumptions and results

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% movement from baseline to healthy value (moderate pathway) or 40% (enhanced pathway).

Emissions and uptake assumptions

Abatement associated with healthier animals occurs for two reasons: a) less animals are required to meet a given level of production and less replacements are required and b) animals will have lower emissions per head as their maintenance energy requirement is reduced (ADAS 2015). In terms of dairy production, improved health levels of 20% and 40% result in an 8% and 16% reduction in the replacement rate under the moderate and enhanced pathways respectively. In terms of suckler beef, there is an 11.2% and 22% reduction in mortality for the moderate and enhanced pathways respectively. This impact of individual measures and their proportional impact is detailed in Table x. A 100% healthy herd would result in 2.25 $MtCO_2e$ less emissions for a given fixed level of output. A 20% and 40% shift towards a healthy herd would therefore result in a 450 $ktCO_2e\ yr^{-1}$ and 900 $ktCO_2e\ yr^{-1}$ reduction.

Table 7. 1: Impact of measures on bovine GHG footprint (recalculated from ADAS 2015)

Measure	kTCO2-e abated	Cost '000 euro	cost euro per tonne basis
Vaccination Pneumonia	8.78	-1735.7	-197.8
Milk routine	72.00	-13082.4	-181.7
Vaccination IBR	207.75	-22696.7	-109.3
Johnes hygiene and Colo management	216.00	-20368.8	-94.3
Dry cow therapy (mastitis)	64.50	-3782.9	-58.7
Johnes buying policy	230.25	-13504.2	-58.7
Fluke treatment	275.25	-12661.5	-46.0
IBR Fencing/purchase policy	169.50	-1364.5	-8.1
Johnes vacc	125.25	-864.2	-6.9
Pnuemonia colostrum intake	9.00	-62.1	-6.9
IBR Carrier id	173.25	-797.0	-4.6
Samonella hygiene	62.25	-71.6	-1.2
Samonella vacc	62.25	0.0	0.0
Fluke - grazing management	210.75	2666.0	12.7
Infertility- fixed time AI	101.25	1863.0	18.4
Pnuemonia - building vent, stock density	6.75	504.6	74.8
Infertility - nutrition	66.00	8045.4	121.9
Infertility - tail paint	50.25	6934.5	138.0
Lameness - cow hardiness	21.00	3695.0	176.0
Scour - cow comfort	0.75	162.2	216.2
Lameness - mobility management	33.75	8073.0	239.2
Scour - prophylactic therapy	1.13	297.6	264.5
Mastitis nutrition	33.38	11092.2	332.4
Lameness - slat mats	45.00	20012.5	444.7
Scour - vacc	1.05	554.2	527.9
Mastitis Housing/milking	18.00	9770.4	542.8
100% healthy	2265.08	-17321.1	-7.6
20% move to healthy	453.02	-32906.4	-72.6
40%move to healthy	906.03	-52730.5	-58.2

Cost assumptions

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 per t CO2-e abated for pneumonia vaccination to the altered housing and milking systems for mastitis reduction (€543 per t CO2-e). Beef costs varied from -721 for colostrum intake/management to reduce pneumonia to altering stocking rates and buying policy for pneumonia (€416 per t CO2-e). The mean marginal costs across these measures were observed to be cost effective with marginal costs calculated at -€49 per t CO2-e abated. The measure reduces GHG per kg product by reducing the need for replacements and an increase in overall production.

Sensitivity analysis

Emissions: As the total biophysical potential of the measure was 2265 ktCO_2e, every 1% shift towards a healthier national herd will decrease emissions by 2.2kt CO_2e.

Inventory inclusion

As this is an efficiency measure, its GHG reduction impact is calculated as the reduction in animal numbers required to maintain the Business-As-Usual production output of meat and milk.

Barriers to uptake

As this measure is made up of a myriad of abatement measures, there is no single barrier to uptake. In terms of animal health, Ireland has already been successful in the eradication in BVD and Animal Health Ireland have undertaken a campaign to eradicate IBR from the herd. Improvement will likely be gradual and linear in nature.

4. Extended Grazing: Both an efficiency and absolute emission reduction measure

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Absolute mitigation	12.8	41.1	22.65	-0.182	-0.632	-15.39
Efficiency emissions reduction	71.8	244.5	130.9	-0.182	-0.632	-2.59
Range	12.8 to 71.8	41.1 to 244.5	127 to 189	-182 to -364	-0.632 to -1.264	-2.59 to -15.39

See A1.4 for full assumptions and results

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 (**Measure 15,** see 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 methane emissions because of improvements in animal productivity as well as reductions in the proportion of dietary energy lost as methane (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 methane 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.

Assumptions

Efficiency - impact on emissions intensity

Dairy: The abatement measure "extended grazing season" is based on studies by Lovett *et al.* (2008). Which compared two sites have 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 (10mm 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 reduces costs to the extent of €3.24 cow^{-1} (Shalloo et al. 2004).

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 inputted into an IPCC national inventory model. Thus, GHG emissions 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. This results in a reduced emissions intensity of 0.025 $kgCO_2e$ $carcass^{-1}$ d^{-1} and a lower relative cost of €0.006 per day extra of grazing for suckler beef systems

Uptake assumptions and Impact on absolute emissions

Assuming that one-third of this area (i.e. 10% of total grassland area) was drained or uncompacted by 2030, it was assumed that this would allow for an extra 80 days of grazing. Extended grazing has both an efficiency component which reduces the emissions intensity of meat and milk, but also an absolute reduction component due to the higher digestibility of fresh grass compared to silage which resulted in 15% lower methane emissions per day of grazing (Jones et al. 2011, Beauchemin et al. 2022). This would result in a reduction in enteric methane of 41 $ktCO_2e$ yr^{-1} or 20% of the full efficiency reduction value

Inventory Inclusion

As with all efficiency measures, the majority of emissions reduction would only be fully reflected if production levels were held constant, as less animals would be needed to achieve the production target. However, there was also an ‘absolute’ reduction associated with reduced methane yield per head.

Barriers to uptake

This measure depends on soil trafficability which in turn depends on a) draining or ‘uncompacting’ soil and b) weather conditions which will vary from year to year. However, it should be noted that climate predictions are for autumn/winters to become warmer and wetter into the future so there may be climate impacts that restrict this measure.

Exchequer costs

Land drainage is currently not eligible for grant-aid and is unlikely to be in the future.

5. Reduced Age of Finishing (bovine): Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	213	470	263.5	-6.99	-6.64	-131.5
Pathway 2	324	732	405	-10.14	-10.18	-124
Range	213 to 324	470 to 732	263 to 405	-6.69 to -10.14	-6.64 to -10.18	-124 to -131.5

See A1.5 for full assumptions and results

Over the period 2010 to 2020 there has been substantial progress made in the age at which bovine animals are finishinged in Ireland. For example in 2010 the average age at which dairy-sired steers were finishinged was 908 days, while in 2020 the corresponding age was 857 days. As a result, enteric and manure methane emissions have reduced by 158 kt CO_2e over that period (Duffy at al. 2022). For most animal categories there has been substantial reduction in the age at which animals are finishinged. Over the period 2010 to 2020, Irish cattle carcass weights remained static. Looking towards 2030 it is possible that such reductions in age at finishing could continue. However, further reductions in age at finishing will likely be associated with a reduction in carcass weights. Without incentives and directly selecting genetically for animals that have a pre-disposition for a reduction in age at finishing, the progress over the next decade is expected to be less that achieved between 2010 and 2020. Mitigation potential is still however substantial.

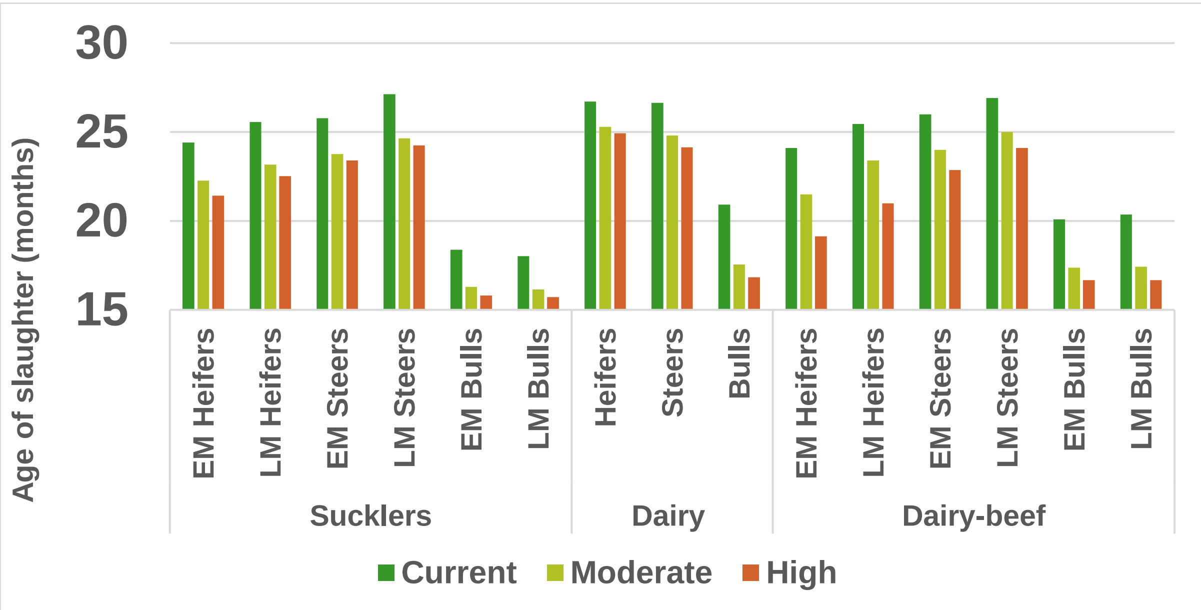

Figure 7.1: Reduction in slaughter age per bovine cohort: Suckler, dairy and dairy-beef sourced early maturing (EM) and late maturing (LM) heifers, steers and bulls (Moderate = Pathway 1, High = Pathway 2).

Uptake assumptions

Pathway 1: Suckler progeny: Early-maturing heifers, steers and bulls mean age of slaughter reduced by 2.05 months on average. Late-maturing steers and heifers mean age of slaughter reduced by 2.45 months on average, late-maturing bull mean age reduced by 1.8 months. Dairy x beef progeny: Early-maturing heifers, steers and bulls mean age of slaughter reduced by 2.4 months on average. Late-maturing heifers and steers mean age of slaughter reduced by 1.95 months on average, late-maturing bull mean age reduced by 3 months. Dairy Heifers, steers and bulls age reduced by 1.6 months on average and dairy bulls slaughter age reduced by 3.3 months.

Pathway 2: Suckler progeny: Early-maturing heifers, steers and bulls mean age of slaughter reduced by a further 0.8, 0.4 and 0.5 months, respectively. Late-maturing heifers and steers mean age of slaughter reduced by a further 0.6 and 0.4 months, late-maturing bull mean age reduced by a further 0.4 months. Dairy x beef progeny: Early-maturing steers and heifers slaughter age reduced by a further 1.1 and 2.4 months, respectively, and EM bulls mean age of slaughter reduced by a further 0.7 months. Late-maturing steers and heifers mean age of slaughter reduced by 0.9 and 2.4 months respectively, late-maturing bull mean age reduced by a further 0.7 months. Dairy heifers, steers and bulls slaughter age reduced by a further 0.4, 0.7 and 0.8 months.

Sexed semen is a process where sperm is differentiated into those containing Y and X chromosomes. This semen is then used for artificial insemination, 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). The impact of the use of sexed semen was used in conjunction with reduction in the age of slaughter, with lower adoption (SS1) used in Pathway 1 and the higher adoption (SS2) used in Pathway 2. The impact of SS1 and SS2 in reducing dairy steers and increasing dairy x beef heifers and steers are shown in Figure 7.2.

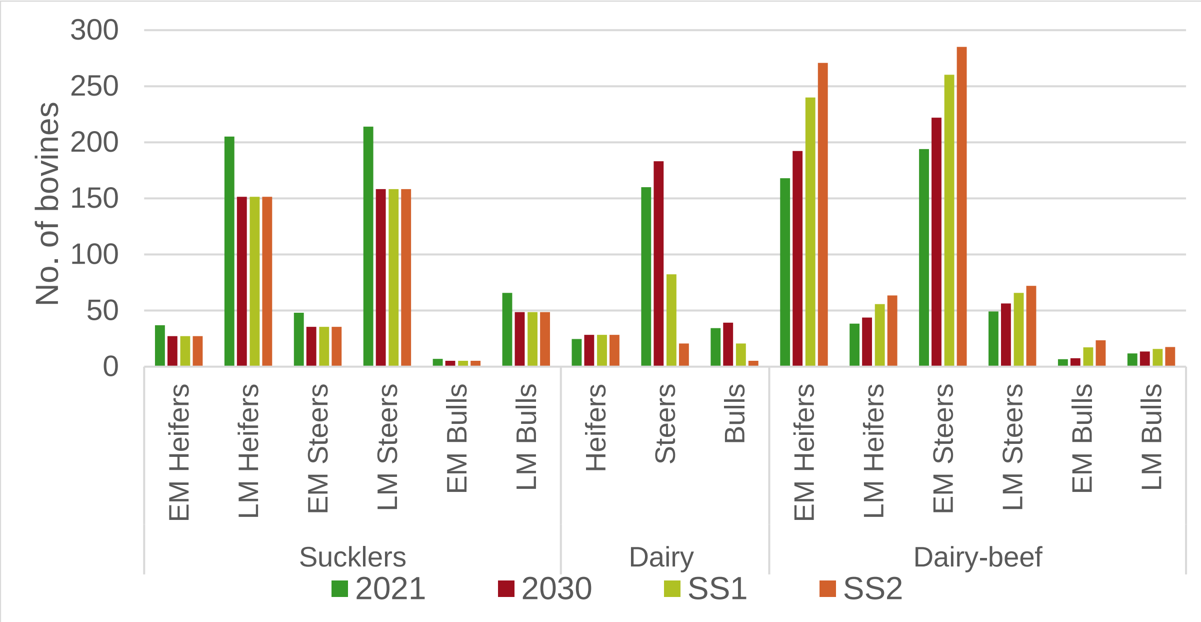

Figure 7.2: Shift in the composition of dairy, suckler and dairy-beef derived heifers, steers and bulls.

Emissions reduction assumptions

There is 168.7 kgCO_2e saving for per month reduction in slaughter age.

Cost Assumptions

The impact on farm profit margin was as follows:

Improvement in net margin by finishing at earlier ages (€/d/head)	
Beef x Beef	€0.76
Beef x Dairy	€0.70
Dairy x Dairy	€0.70

Inventory Inclusion

Reduced age of slaughter will appear in the inventory as a reduction in animal numbers from across the above cohort of bovines between the July and December animal census.

Barriers to Uptake

There is resistance to early finishing from a cohort of farmers, particularly those operating extensive finishing systems with later maturing breed types. Finishing with lighter animals while also demonstrating the gain in margin will be key to measure success.

6. Liming: Absolute emissions reduction

Pathway	Abatement in 2025 (ktCO₂e yr⁻¹)	Abatement in 2030 (ktCO₂e yr⁻¹)	Mean abatement (ktCO₂e yr⁻¹)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	25.4	111.5	38.1	-6.74 (Low) -15.77 (High)	-18.66 (Low) -40.85 (High)	-167 (Low) -366 (High)
Pathway 2	36.9	162	55.3	-10.19 (Low) -22.84 (High)	-27.10 (Low) -72.61 (High)	-167 (Low) -448 (High)
Range	25.4 to 36.9	111.5 to 162	38.1 to 55.3	-6.74 to -22.84	-18.66 to -72.61	-147 to -448

See A1.6 for full assumptions and results

Measure description

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 and soil nutrient availability and fertiliser efficiency and crop productivity 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 60kg 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 three growing seasons (Wall et al., 2018). Lime application may also modify soil microbial communities (Goulding, 2016) and increase organic matter (OM) inputs (Fornara et al., 2011; Jokubauskaite et al., 2016) with the effect of increasing soil carbon stocks (Fornara et al., 2011, Carolan & Fornara 2016). The change in microbial community also alters the N_2/N_2O ratio during denitrification, thereby affecting N_2O emissions (O'Neill et al. 2022, Žurovec et al. 2022).

Emissions Assumptions:

- Mean lime application rate is 5 tonnes per hectare, applied every 4 years. The change in pH from 5.5 to 6.6 releases 70 kg N and 5.3kg P. It was assumed that on dairy grassland, this displaced 70kg mineral fertiliser, while it displaced 30kg on non-dairy grassland. As there was a 70:30 split between dairy and non-dairy, 57kg per hectare on-average was displaced.
- There is also a reduction in N_2O EF of 20.6% associated with this change in pH (O'Neill et al. 2021).
- There is an Increase in SOC of 0.5 tCO_2e ha^{-1} yr^{-1} (see Measure 18. Grassland sequestration, Carolan & Fornara 2016, Poeplau et al. 2019).

Uptake Assumptions:

- **Pathway 1:** 2m tonnes lime spread by 2030 with 752,271 ha limed by 2030 with linear uptake distribution
- **Pathway 2:** 2.5m tonnes lime spread by 2030 with 1.09 million ha limed by 2030 with linear uptake distribution

Cost Assumptions

Soil Sampling Costs: A soil sample should be taken for every 3 hectares of land targeted under this pathway at a cost of €25 per sample to be tested in the laboratory (Teagasc, 2020b).

Liming Costs:

- Low cost scenario – Fuel (for spreading) = €0.53/l, N/P fertiliser replacement value N = €1.20, P =€2.62, Lime = €25 per tonne including labour cost
- High cost – Fuel (for spreading) = €1.30/l, N/P fertiliser replacement value N = €2.70, P =€3.84, Lime = €35 per tonne including labour cost

Sensitivity analysis

Emissions reduction: This measure is sensitive to uptake rate and the type of fertiliser being replaced with mitigation ranging from 17.4 kTCO_2-e (assuming that all fertiliser replaced was a urea product) to 111.5 kTCO_2-e (assuming full CAN replacement with full uptake occurring in 2021). In addition, the total mitigation is reduced by 50% in the absence of the CO_2 EF of lime being refined to Tier 2 levels.

Costs: Primary cost sensitivities are (in order) a) price of mineral fertiliser, b) cost of lime, c) the cost of soil sampling, d) the cost of fuel and e) the cost of labour

Inventory Reporting and Requirements

The reduction in N_2O can be reflected in the inventory by the reduction in fertiliser emissions. The impact of pH on N_2O EF. This will require field-level reporting on soil pH. A revised EF is required for lime in order to obtain the full benefit of this measure.

Barriers to Uptake

The benefits from optimising soil pH are well established. However, a significant portion of farmers habitually do not lime their land (Buckley et al., 2018) or test their soil to establish their land's pH levels. Derogation farms and farmers in the Green, Low-Carbon, Agri-Environment Scheme (GLAS) are required to soil test regularly (every 4 years) and to follow a farm nutrient management plan. The usage of lime as increased in response to the increase in fertiliser price, and there was over 1 million tonnes of lime sold last year (CSO 2022). However, barriers remain, particularly the use of the con-acre model of short-term land leasing may be a significant impediment to adoption of this measure as farmers renting land on an annual lease hold basis may be less inclined towards optimal soil fertility (Bellon & Lamine 2009).

Exchequer costs

Liming is currently being grant-aided at €8M

7. Clover & Multispecies Swards: Absolute emissions reduction

Pathway	Abatement in 2025 (ktCO₂e yr-1)	Abatement in 2030 (ktCO₂e yr-1)	Mean abatement (ktCO₂e yr-1)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	96.76	193	96.7	-17.26 to -3.696	-34.51 to -7.393	-121 to -25.84
Pathway 2	143	286	143	-11.31 to 1.723	-22.63 to 3.44	-79.09 to 12.06
Range	96.76 to 143.1	193 to 286	96.7 to 143	1.723 to -17.26	3.44 to -34.51	12.06 to -121

See A1.7 for full assumptions and results

N_2O emissions arising from the use of synthetic N fertilisers can be reduced by relying more on biologically fixed nitrogen in crop production. Biological nitrogen fixation occurs in N fixing crops (legumes) form symbiotic relationships with bacteria (Rhizobia) in the soil that allows them to transform atmospheric N_2 to N compounds and use this in place of N provided by synthetic fertilisers. Besides the fixed N supporting the growth of the legume crop (e.g. clover), part of these N compounds also become available to the grass plants, reducing their need for synthetic N. This effect becomes substantial above a clover content of around 20%-30% in the sward. The effect is robust and persistent across legume species and climatic regions, as shown by a series of experiments in Europe over three years, where savings of 300 kg N ha-1 were achieved without compromising the yield, though grass-clover pastures tend to receive very low level of N and therefore their yield on average can be lower than highly fertilised grass swards (see a review in Lüscher et al. 2014). Evidence suggests that the biological fixation itself does not lead to significant emissions – the IPCC 2006 recommendations (IPCC 2006) removed legumes as a source of direct N_2O emissions. Forage legumes might also be capable or reducing enteric CH4 emissions, partly through their condensed tannin content (Jayanegara et al. 2012), though the evidence is not conclusive.

The growth pattern of the grass-clover sward is different from grass-only swards, as clover requires higher temperature for growth, delaying the peak growth by a month, but providing higher yields (and better digestibility) later in the season. Furthermore, the protein content of clover is higher than perennial ryegrass; a 20% clover content increasing the protein content of the silage 2%. Mixed swards containing multiple species of grass and legumes show higher yield than average monocultures (though lower than the best performing monocultures) (Kirwan et al. 2007, Finn et al. 2018), and drought tolerance due to deep-rooted species in the mix – an important aspect in adapting to the changing climate, particularly in south England (Cummins et al. 2020, Finn et al. 2018). Furthermore, multi-species swards may enhance C sequestration due to the higher relative root biomass and the deep-rooting of some species which delivers carbon deeper into the soil (Tilman et al. 2012, Fornara & Tilman 2012).

Upon establishing the grass-clover mix by using a seed mixture high in clover, the mix needs to be maintained, as over the years the clover tends to be outcompeted by the grass, particularly if more N is added than the recommended low levels. Good management includes preventing poaching and adjusting grazing and fertilisation to balance clover and grass growth.

Emissions Assumptions:

- 20-30% Clover is assumed in the sward –reducing N fertiliser by 70kg N yr^{-1} on dairy farms and 30 kg N yr^{-1} on non-dairy farms. It is assumed that organic farms apply no inorganic fertiliser N.
- There are no N_2O emissions associated with biological N fixation (IPCC 2019).
- Reductions appear in the inventory as reduced fertiliser inputs
- Increase in SOC = 0.5 tCO_2e ha^{-1} yr^{-1} (see Measure 18)

Uptake Assumptions

- **Pathway 1:** Reseeding rate of 6% on dairy and 1% on non-dairy farms with an uptake rate of 35% on dairy and 25% on non-dairy farms with a total of 505kha sown by 2030
- **Pathway 2:** Reseeding rate of 10% on dairy and 3% on non-dairy farms with an uptake rate of 70% on dairy and 50% on non-dairy farms, resulting in 1.25 Mha sown by 2030
- Uptake assumed to be linear as technology is known

Cost Assumptions

- *Low cost scenario* – Clover seed was priced at €12 ha^{-1} with a seed rate of 5kg ha^{-1}. Contractor rates of €118 per hectare are assumed for reseeding of grassland with clover (FCI, 2022). Fuel (2.5l per hectare for spreading if seed is broadcast) was €0.53 l^{-1}. Under the low cost scenario, the mean N fertiliser replacement value was set at €1.20 kg^{-1} N. After five years, re-seeding was assumed to be required, with seed oversown b the farmer. As a result, no labour cost was assumed.
- *High cost scenario* – Multispecies seed was priced at €66 per 12 kg bag with a seed rate of 30 kg ha^{-1}. Fuel (2.5l per hectare) was priced at €1.30 l^{-1} with an assumed N fertiliser replacement value N of €2.70 kg^{-1} N. Partial re-seeding by over-sowing was assumed to occur after five years at half the seed rate. No labour cost was assumed.

Sensitivity analysis

- *Emissions reduction:* This measure is sensitive to uptake rate and the type of fertiliser being replaced with a three-fold difference in the mitigation value if protected urea was assumed to be replaced compared to CAN. Also farm typology had a large impact, as dairy farms have a larger N fertiliser application rate that can be replaced.
- *Costs:* Primary cost sensitivities are (in order) a) price of mineral fertiliser, b) cost of clover or multi-species sward seed, c) the cost of fuel and d) the cost of labour. The variation in total net costs ranged from €+13.31M to €-87M.

Inventory Reporting and Requirements

The reduction in N_2O is principally reflected in the national inventory by the reduction in fertiliser emissions. Clover or multi-species sward uptake can be recorded either via seed sales and/or earth observation techniques.

Barriers to Uptake

In order to establish clover in the sward, soil pH and soil P/K levels need to be correct. Therefore Measures 1 and 2 must be in place in order for this measure to be implemented, unless soil pH and P levels are naturally high. The establishment of both multi-species swards and clover also requires a high level of sward management, which is a cost in terms of farmer time, which can be especially problematic for many livestock farmers, who hold other jobs and farm part-time. In addition, bloat commonly occurs in clover or legume-rich swards. This results in the build-up of gases within the rumen as fermentation takes place. This can be prevented by either the addition of hay can be a good source of fibre or the addition of bloat oil to water.

Exchequer Costs

If the €50 per acre scheme (€125 per ha) were to be extended out to 2030, the exchequer cost would be as follows:

Pathway 1 – 472.080 ha sown – €63.13M

Pathway 2 – 757,440 ha sown – €157.8M

8. Impact of Improved Soil P levels on the N_2O emission factor: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	13.63	58.15	36.56	9.16 (low) 13.54 (high)	12.06 (low) 17.81 (high)	220.2 (low) 325.3 (high)
Pathway 2	29.99	116.3	73.57	20.16 (low) 29.78 (high)	24.12 (low) 35.63 (high)	207.4 (low) 306.4 (high)
Range	13.65 to 29.9	58.15 to 116	36.56 to 73.57	9.16 to 29.78	12.06 to 35.65	207 to 325.3

See A1.8 for full assumptions and results

Low P soils have been shown to have significantly high N_2O emissions associated with both organic and mineral N compared to higher P level soils (O'Neill et al. 2022). This may be related to shifts from microbial to fungal microbiota at low P levels (Gebremichael et al. 2022, O'Neill et al. 2020). The most sustainable way to increase P levels is via application of animal manures.

Emissions Assumptions

- There is a 10% reduction in the N_2O EF associated with shift in P index
- There are 57% of soils at P index or P index 2 (Wall & Plunkett 2018).

Uptake Assumptions

Pathway 1: It was assumed that 15% of soil index 1 and 15% of soil index 2 were brought to soil index 3 and that it takes three years to shift one soil P index. Uptake was assumed to be logarithmic due to the lag time required to shift P index.
Pathway 2: It was assumed that 30% of soil index 1 and 30% of soil index 2 were brought to soil index 3 and that it takes three years to shift one soil P index. Uptake was assumed to be logarithmic due to the lag time required to shift P index.

Cost Assumptions

- An extra 50kg P was required to build soil fertility from Index 1 to Index 3
- An extra 30kg P was required to build soil fertility from Index 2 to Index 3
- Under the low cost scenario the cost of P was €2.62 per kg^{-1}P, while under the high cost scenario, the cost was €3.87 per kg^{-1}P.

Sensitivity Analysis

- *Emissions reduction:* This measure is sensitive to uptake rate and the type of fertiliser being replaced with a three-fold difference in the mitigation value if protected urea was assumed to be replaced compared to CAN. Also farm typology had a large impact, as dairy farms have a larger N fertiliser application rate that can be replaced.
- *Costs:* Primary cost sensitivities are (in order) a) price of mineral fertiliser, b) cost of clover or multi-species sward seed, c) the cost of fuel and d) the cost of labour. The variation in total costs ranged from €-67M to €-220M.

Inventory and Reporting requirements

This measure requires that an adjustment is made for the N_2O EF dependent on soil P index. This measure requires field-level soil testing, which should be performed as part of a nutrient management plan.

Barriers to Uptake

The growth response of Grass/crops to Phosphorus fertiliser application is not always as obvious or immediate as the response to nitrogen. The current high price is also a barrier.

Exchequer Costs

There are no eligible exchequer costs and none are likely

9. Reduced Crude Protein in Bovine and Porcine Diets: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	36.08	45.10	31.60	-2.52 to -0.87	-5.04 to-1.62	-112 to -35.88
Pathway 2	53.41	93.13	49.68	-5.43 to -2.13	-10.78 to -3.94	-116 to +42.25
Range	36.08 to 53.41	37.58 to 93.13	31.60 to 49.68	-0.87 to -5.43	-1.62 to -10.78	-116 to +42.25

See A1.9 for full assumptions and results

These strategies have the advantage that they can reduce manure emissions from both storage and upon application to the land. Reducing crude protein (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).

Bovine diets: Crude protein content was assumed to be lower by 2% during the housing period.
Porcine diets: Crude protein levels in diets were lowered by 3% with supplemental amino acid fed.

Emissions Assumptions

- Based on research by Shalloo et al (2018) and O'Brien (2018), 17% of the total dairy cow diet is assumed to be derived from concentrates and the average crude protein percentage of these concentrates is set at 17%. Results from the Teagasc National Farm Survey indicated that, between 2014 and 2018, the average dairy cow was fed 1,045 kg of concentrates. This is assumed to hold for the study period to 2030. At this concentrate intake rate a 1 percentage point reduction in the crude protein content of dairy concentrates is associated with a 1.5 kg reduction in the N excretion rate of bovines (O'Brien & Shalloo, 2019).
- Pigs: Each 1% reduction in crude protein resulted in a 7.5% reduction in N excretion (Ball et al. 2013, 2016).
- No impact on enteric methane was assumed. There are conflicting data on the impact of carbohydrate/protein ratio on enteric methane emissions as well as decreased dissolved ammonia which can increase slurry pH, thus increasing manure methane.

Uptake Assumptions

Bovine

Pathway 1: Uptake rates were assumed to be 40% across both dairy and beef.

Pathway 2: Uptake rates were assumed to be 90% across both dairy and beef

Only protein content during the housing period was considered. A sigmoidal uptake response was assumed. A general reduction in the crude protein content of feed formulation could increase both the uptake rate and total uptake percentage of this measure.

Pigs

Uptake rates of 40% (**Pathway 1)** and 90% (**Pathway 2**) by 2030 with a linear uptake response assumed as implementation would be easier given the high percentage feed costs in the sector. Pathway 2 assumes that virtually all feed manufacturers reduce the crude protein content of feed. It was assumed that a 0.95% lysine/methionine was supplemented into the diet.

Cost Assumptions

- *Bovines:* A reduction in the protein content (17% -15%) was assumed to reduce feed costs by €3 per tonne or €1.35 per LU.
- *Pigs:* The cost of the crude protein was assumed to vary between +€2 and -€4.58 per pig depending on a) the relative cost of soybeans to amino acids and b) costs required for two-phase feeding. The mean cost per pig was calculated at -€1.92 per pig.

Sensitivity Analysis

- *Emissions reduction:* The main source of uncertainty is the rate of uptake and the final total uptake rate. Pathway 1 was 37% and 40% for bovines and pigs respectively while final uptake rates were 80% and 90% for bovines and pigs respectively. This higher uptake rate would entail all feed manufacturers reducing the crude protein content of feed.
- *Costs:* The primary cost sensitivities are the relative costs of crude protein and supplemental amino acids. The cost variation was estimated to vary between €-29 and €-112 $tonne^{-1}$ CO_2e abated.

Inventory and Reporting requirements

This measure will appear in the inventory as a reduction in N excretion and will impact on the full N cascade, resulting in lower direct N_2O emissions from manure management and manure land-spreading. In addition, reductions indirect N_2O associated with a) ammonia from housing, storage and spreading of liquid and solid manures and b) N leaching upon slurry/FYM spreading will occur.

Barriers to Uptake

Historically livestock farmers in Ireland have tended to associate crude protein content in concentrates with feed value despite feed energy usually being the first-limiting nutrient in grazing systems. Dairy cows do require concentrate supplements with a higher crude protein content during periods where silage is fed (11-12% crude protein is associated with grass silage (2016). However, the requirement for supplementary protein is reduced when animals are grazing fresh pasture (16-28% crude protein is associated with grazed grass (Kavanagh, 2016). This is well understood within the industry and is accounted for in ruminant nutrition models, yet in many instances it is not reflected in farm management decisions on the ground.

A concerted effort is required by knowledge transfer agents and the wider industry to persuade farmers of the need to reduce crude protein in dairy cow concentrates. Given the cost benefit to farmers, the lack of any adverse effect on herd performance and simplicity to implement, this measure can achieve widespread adoption in a relatively short timeframe (>50% herds in <24 months). However, a number of steps are needed to deliver this change. Initially, a collaborative campaign to better inform farmers and the wider industry on the practical fundamentals of protein and energy requirements in ruminants is required. Also, more regular inclusion of pasture/silage feed quality information (energy, protein, fibre) in routine KT activities would highlight the nutritional value and balance of high quality pasture at different times during the grazing season. Furthermore, the traditional use of crude protein as 'shorthand' for concentrate quality needs to be phased out with the cooperation of the feed manufacturing industry. Its current use may be explained in part by the mandatory declaration of proximate analysis of crude protein on feed labels.

Exchequer Costs
There are no eligible exchequer costs and none are likely

10. Altered fertiliser formulation: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Protected Urea						
Pathway 1	100.1	272	100	-4.62 to -1.47	-19.52 to -7.10	-71.64 to -26.08
Pathway 2	121	273	136	-8.475 to -3.04	-20.91 to -7.74	-58.64 to -21.71
Protected urea + nitrification inhibitor (Path2)	0	113	17.3	0	1.69 to 3.37	14.96 to 29.91
Range	0 to 121	113 to 273	17.3 to 136	-8.475 to -1.47	-20.91 to 3.37	-71.64 to +29.91
Compounds						
Pathway 1	64.9	145	72.3	0	0	0
Pathway 2	73.4	167.4	94.2	0	0	0
Range	64.9 to 73.4	145 to 167.4	72.3 to 94.2			

See A1.10 for full assumptions and results

NBPT/NPPT- protected urea & Replacement of nitrate-based with ammonium-based compounds

Urea is a source of ammonia emissions, with 18% of applied urea assumed to volatilise to gaseous ammonia. Urea applied to agricultural land reacts with soil water and the enzyme urease, which hydrolyses urea-N to ammonium-N. During this hydrolysis process N losses occur through ammonia gas volatilisation to the atmosphere (Bouwman et al. 2002). This ammonia is also a source of indirect N_2O. In addition, the direct N_2O EF of urea has been observed to be low (0.25%) across a range of soil types compared to CAN (1.4%, Harty et al. 2016, Roche et al 2016). This is due to the fact that urea must be transformed via ammonification and nitrification to nitrate before N_2O from denitrification processes can occur. Urea, protected with either NBPT or NPPT has been demonstrated to reduce both ammonia and N_2O loss. Ammonia was reduced by by 80% relative to straight urea, with an N_2O EF of 0.4%, which is far lower than that of CAN (Forrestal et al. 2016, Harty et al. 2016). Similarly, recent data has shown that ammonium-based compounds (eg. 18-6-12) has an N_2O EF that is 40% lower compared to high nitrate compounds (eg. 27-2.5-5, Gebremichael et al. 2021).

Emissions Assumptions

- The mineral fertiliser N_2O emission factor (EF_1) of Urea +NBPT is 0.4% (3.5 times lower) compared to CAN N_2O EF_1 of 1.4% (Harty et al. 2016, Roche et al. 2016).
- The mineral fertiliser N_2O emission factor (EF_1) of Urea +NBPT+DCD is 0.1% (over 10 times lower) compared to CAN N_2O EF_1 of 1.4% (Harty et al. 2016, Roche et al. 2016).
- The mineral fertiliser N_2O emission factor (EF_1) of straight urea is 0.25% compared to protected urea EF_1 of 0.4% (Harty et al. 2016, Roche et al. 2016).
- Low nitrate compounds have 40% reduction in N_2O EF compared to high nitrate compounds (N_2O EF_1 = 1.4%, Rahman & Forrestal 2021).

Uptake Assumptions

Pathway 1

- Straight CAN to protected urea: 65% of CAN is assumed to be replaced with protected urea (linear uptake response). All urea replaced by protected urea by 2027 (sigmoidal response).
- Compound fertilisers: A total of 50% of high CAN low PK compounds (e.g. N-P-K: 27-2.5-5, 24-2.5-10) are replaced with ammonium-based compounds
- Linear uptake to 2030 of both measures was assumed as it is a proven mature technology

Pathway 2

- Straight CAN to protected urea: 75% of CAN is assumed to be replaced with protected urea (linear uptake response). All urea replaced by protected urea by 2027 (sigmoidal response).
- 20% of CAN replaced with protected urea with a nitrification inhibitor in the melt.
- Compound fertilisers: A total of 65% of high CAN low PK compounds (e.g. N-P-K: 27-2.5-5, 24-2.5-10) are replaced with protected urea.
- Linear uptake to 2030 of both measures was assumed as it is a proven mature technology

Cost Assumption

The following cost assumptions are made for replacing urea or CAN with protected urea

Low cost	**N (%)**	**Cost /kgN (€)**
Urea	46%	0.95
Protected urea	46%	1.08
CAN	27%	1.20
Protected urea + NI	27%	1.27
High cost	**N (%)**	**Cost /kgN (€)**
Urea	46%	2.06
Protected urea	46%	2.34
CAN	27%	2.60
Protected urea + NI	27%	2.76

The replacement of nitrate-based with ammonium-based compounds was considered to be cost neutral as there is little cost differential between products and where there are, these variations occur in both directions.

Sensitivity Analysis

- *Emissions reduction:* The main source of uncertainty includes the impact of soil type and land-use. Studies by Harty et al. (2016) and Roche et al. (2016) demonstrated a four-fold difference in CAN emissions and two-fold difference in urea emissions dependent on soil type, while a 4 to 10-fold difference was observed.
- *Costs:* The primary cost sensitivity is the relative cost of CAN, protected urea and straight urea.

Inventory and Reporting requirements

The EF's associated with straight urea, protected urea and CAN are already incorporated into the national inventories. The EF's associated with ammonium – based and nitrate-based compounds are currently being studied across a number of soil types.

Barriers to Uptake

The main uptake barrier for protected urea has been availability. To date, availability has been limited and supply was outstripped by demand. Previously, concern was been expressed about potential residues from protected urea; however no residues have been detected in produce (Nkwonta et al. 2021).
Finally, protected urea has greater nitrogen use efficiency compared to straight urea; hence, the substitution will facilitate a reduction in chemical N application rates. Informing and convincing farmers to reduce application rates will require knowledge transfer initiatives and promotion.

Exchequer Costs
There are no eligible exchequer costs and none are likely

11. Adding Dietary Lipids: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	9.67	66.84	24.53	2.80 to 4.03	5.83 to 8.87	87.20 (rape) 133 (linseed)
Pathway 2	19.27	125.33	46.75	3.46 to 5.27	10.9 to 16.6	87.20 (rape) 133 (linseed)
Range	9.67 to 19.27	66.8 to 125.33	24.53 to 46.75	1.77 to 5.10	6.16 to 16.24	87.20 to 133

See A1.11 for full assumptions and results

Increasing the proportion of unsaturated fatty acids in the diet can reduce methane emissions. This reduction occurs due to a) inhibition of a proportion of the rumen microbes, b) acting as a hydrogen sink and c) partially replacing feed that is digested in the rumen with feed components which are digested in the intestine (Martin et al. 2010, Boland et al. 2020). From the various possible supplementary fat sources (various whole seeds and plant oils) the use of whole rapeseed or whole linseed is most widely researched (Boland et al. 2020).

Emissions Assumptions

- Extruded linseed or rapeseed is assumed to reduce methane emissions by 4% ± 1% with 100g/kg linseed or rapeseed in diet (Pellerin et al. 2013, Hammond et al. 2015, McBride et al. 2015, Boland et al. 2020). In a recent study in Teagasc Grange, dietary supplementation of dairy beef bulls with linseed oil (4% inclusion) mixed into a course ration fed twice a day reduced methane emission (CH_4 g/day) by 18% (Roskam et al., 2023).
- This can be incorporated in the inventory as either a) a direct reduction in absolute methane emissions (CH_4 g/day) or b) a % reduction in the methane emission factor (Y_m) for dairy cows/heifers.
- No impact on productivity was assumed. Animals on high lipid diet exhibit lower dry matter intake but no reduction in milk yield (Hristov *et al.,* 2022).

Uptake Assumptions

Unsaturated fatty acids can be incorporated into a concentrate diet either on farm (where facilities exist) or at the feed mill, but it is not practical in situations where animals are not being fed supplemental concentrate while grazing (beef animals).

- ***Pathway 1:*** The uptake rates were assumed to peak at 8% of dairy cows
- ***Pathway 2:*** The uptake rates of 15% were assumed for dairy cows/heifers

- Strongly Sigmoidal uptake response was assumed with the majority of uptake occurring post 2025.

Cost Assumption

The fat content of the cultivated linseed or rapeseed varieties is 460 g/kg DM (INRA et al. 2015), and the fat content of the standard concentrate animal feed is 75g/kg DM, therefore 78g/kg DM of the diet has to be replaced by rapeseed. Assuming that the price of cracked rapeseed is €430 t fresh matter^{-1} and linseed is €510 t^{-1} and the price of concentrate is €320 t fresh matter^{-1}. Thus the cost of diet change is €8.6 t DM^{-1}, or €36 per head for rapeseed.

Sensitivity Analysis

- *Emissions reduction:* The main sources of uncertainty is the uptake rate and the emissions reduction per unit fatty acid incorporated into the diet. The range for the efficacy of the measure ranged from a 2.9% to 4.8% reduction per 1% increase in fatty acid inclusion.
- *Costs:* The primary cost sensitivities are between whether linseed or rapeseed meal is used with a price variation of €36 to €56 per head.

Inventory and Reporting requirements

This measure can be expressed in the inventory as either a percentage reduction in total methane emissions *per hea*d or a direct reduction in the methane emissions factor (Y_m).

Barriers to Uptake

Developing a convincing economic model: taken as a whole, current research suggests that measurable increased production responses are unlikely to occur. Therefore fatty acid supplementation will therefore constitute an extra cost, without affecting production in any way. Thus, alternative methods need to be developed to incentivise the use of what are likely to be expensive additives to decrease ruminal methane production.

Exchequer Costs

There are currently no exchequer costs, although these are likely to be required in order to incentivise uptake.

12. Feed additives: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	11.78	372	168.6	0.882 to 1.06	38.33 to 54.12	103 to 145
Pathway 2	10.51	788	293.8	0.315 to 0.484	53.87 to 92.61	68.4 to 117.5
Range	5.8 to 11.78	197 to 788	55.4 to 293.8	0.315 to 0.882	38.33 to 92.61	68.4 to 145

See A1.12 for full assumptions and results

A variety of dietary manipulations have been proposed to reduce enteric methane emissions in cattle (Hegarty et al., 2021; Beauchemin et al., 2022) with limited success mainly due to the requirement of continuous feeding and therefore no viable option available for grazing systems. Indeed, the International report coordinated by Global Research Alliance, evaluating efficacy and applicability of methane inhibiting feed additives for livestock, identified the major constraints for delivery as 'insufficient evidence of a co-benefit of increased production' as well as 'a reliance for additives to be mixed into a total mixed ration and fed continuously with little options for extensive or grazing systems' (Hegarty et al., 2021). This latter point was also emphasised in an international report by the Technical Advisory Group on enteric methane of FAO LEAP Partnership 2022, which concluded that 'more research is needed to develop, adapt, and evaluate anti-methanogenic strategies for grazing systems' (FAO, 2022; Beauchemin et al., 2022).

Major progress in the development of nutritionally based solutions to reduce enteric methane emissions, has been made as part of projects such as the SFI Centre 'Vistamilk' and 'Meth-Abate' (DAFM funded) which have evaluated many supplements including 3-NOP, seaweeds, oils and novel rumen oxidising agents. *Ascophyllum nodosum* (ASC), an indigenous brown seaweed that is found in abundance on Irish coastlines, and a treatment of ASC (seaweed extract) generated to improve palatability and shown to include phlorotannins were assessed for their abiity to reduce methane in beef cattle. Treatment with the brown seaweed tended to reduce methane by 4% and the extract by 7%. However the extract reduced average daily gain relative to the unsupplemented animals (Roskam et al., 2023).

Dietary Supplementation with Halides (Oxidising Methane Inhibitors)

A particularly potent potential target for feed additives is the rumen Oxidative Reduction Potential (ORP), a parameter which influences methane production rates. In a recent trial in Teagasc Grange with 80 beef cattle over a 70 day period, a pelleted format of an Oxidising Methane Inhibitor commercially known as RumenGlas (2.25% CaO2) reduced methane by 28% with no negative effects observed on animal performance or health metrics. Research continues on the development of potential slow-release forms of CaO_2 have been deemed suitable to progress to bolus or pellet formats, enabling a longer-lasting effect in the suppression of methanogenic microorganisms within the rumen, facilitating application in pasture-based production system. Grazing trials will have to be performed to confirm their effectiveness while animals are at pasture. The RumenGlas product while showing evidence of efficacy in indoor systems will have to be approved by EFSA prior to sale in the EU. This process has commenced but will take some time to complete.

Dietary supplementation with 3-NOP:

3-Nitrooxypropanol, (3-NOP), is a synthetic non-toxic organic compound that inhibits the enzyme methyl coenzyme M reductase (MCR), which catalyzes the final step in methanogenesis. Its commercial name is Bovaer and is produced by the company DSM. It is a promising methane inhibitor in that its supplementation results in a consistent methane yield decrease of ~30% in many trials across the world (Martinez-Fernandez et al., 2014; Haisan et al., 2017; Romero-Perez et al., 2014; Jayanegara et al., 2018). Microbial community analyses has demonstrated that 3-NOP was able to shift activity away from methanogenic bacterial species found in the digestive tract towards Prevotella and Succiniclasticum species, which are able to benefit from the excess hydrogen. The lowest proposed commercial dose of 3-NOP (60 mg/kg DM of the total daily ration) when applied to TMR can reduce methane emissions from dairy cows by 22–35%. In a recent study in Teagasc Grange, dietary supplementation with 3-NOP reduced enteric methane emissions by 30% in growing beef cattle offered a forage based TMR diet in a 12-week indoor trial (Kirwan et al., 2023) with negative effect on performance or animal health.

Further work is ongoing on introducing these additives into the diet of grazing animals. Preliminary results from research in Moorepark is indicating that there is an 8% reduction in methane when 3-NOP was fed to animals during milking (Lahart et al. 2022).

Emissions Assumptions

- ***Indoor feeding***: A 30% reduction in methane emissions was assumed upon additive introduction to beef cattle indoors (Kirwan et al., 2023); A 25% reduction was assumed for autumn calving dairy cows indoors and a 15% for spring dairy cows fed with 3-NOP indoors
- ***Grazing:*** Methane from grazing dairy cows and heifers was assumed to be reduced by 7% upon 3-NOP feeding during milking (Costigan et al. 2022)

Uptake Assumptions

Pathway 1

Indoor feeding: This measure was assumed to be applicable to 20% and 60% of spring-calving and autumn-calving dairy cows respectively with 70% of beef cattle having feed additives introduced into indoor diets.

Grazing cows: 40% of dairy cows were assumed to be fed with 3NOP, equating to the majority of cows in derogation. Uptake of this measure was only assumed to occur post-2025, with a steep linear uptake of this measure to 2030.

Pathway 2

Indoor feeding: This measure was assumed to be applicable to 30% and 70% of spring-calving and autumn-calving dairy cows respectively with 70% of beef cattle having feed additives introduced into indoor diets.

Grazing cows: 60% of dairy cows were assumed to be fed with 3-NOP, equating to the majority of cows in derogation. In this scenario, 3-NOP is assumed to have a 20% efficacy in terms of methane reduction. Uptake of this measure was only assumed to occur post-2025, with a steep linear uptake of this measure to 2030.

Cost Assumption

Costs were assumed to range from €25.55 for beef cattle during housing to €60.59 for dairy cows (year round). This assumed a cost of €80 per kg product (Table 7.2).

Table 7. 2: *Costs associated with 3-NOP*

	3-NOP dosage (kg/year)			Cost 80 euro per kg	Total cost
	g/kgDMI*	kgDMI/day	kgNOP/year	per cow	
Dairy cow	0.125	16.6	0.76	€60.59	€41,934,829
Suckler cow	0.125	9.3	0.42	€33.95	
Beef	0.125	7	0.32	€25.55	€3,008,640
Total					€44,943,469
Euro per tonne					113.95

Sensitivity Analysis

- *Emissions reduction:* The main source of uncertainty is the situation in which 3-NOP is deployed. As 3-NOP has to be fed continuously (due to a high breakdown rate once ingested), efficacy in grazing situations is limited to periods of milking. A meta-analysis has demonstrated a range of 20% to 40% reduction in methane yield associated with indoor-fed animals (Dijkstra et al., 2018).
- *Costs:* The costs of the product are relatively unknown but will probably not vary considerably due to there being a sole supplier.

Inventory and Reporting requirements

The EF's associated feed additives are not currently in the National GHG Inventories, but could be easily incorporated into the national inventories based on the amount of feed additive sold.

Barriers to Uptake

The main barrier is cost. As there is no economic or production benefit from introducing 3-NOP, an incentivisation scheme or an alternative economic model that monetises GHG reduction will be required. Otherwise 3NOP will constitute an extra cost on the farmer which will retard uptake rates. There are uncertainties as feed additives are subject of ongoing research and this may identify barriers to adoption such as delivery mechanisms, animal palatability, meat and milk residues, farmer/industry/consumer acceptability.

Exchequer Costs

There are currently no exchequer costs, although these are likely to be required in order to incentivise uptake.

13. Low emission slurry spreading: Absolute emissions reduction

Pathway	Abatement in 2025 (ktCO2e yr^{-1})	Abatement in 2030 (ktCO2e yr^{-1})	Mean abatement (ktCO2e yr^{-1})	Cost 2025 (million €)	Cost 2030 (million €)	Mean € per tonne CO2e
pathway 1 & 2	76.8	87	72.9	20.9	23.7	€363.79
Range	77.5 to 86.6	102 to 107	74.3 to 82.5	11.1 to 34.6	13.2 to 40.4	128 to 400

See A1.13 for full assumptions and results

Low emission slurry spreading techniques (LESS) are based on the principle of reducing the area of the ammonia emitting surface, in this case soil / plant surface that is covered by the applied liquid manure, and can reduce ammonia emissions by more than 50% when compared to emissions associated with the use of splash plate methods (Thorman et al. 2008). Low emission slurry spreading by *dribble bar* or *trailing hose* reduces the ammonia volatilising surface area by depositing slurry on top of grass in bands rather than broadcasting over a larger surface area. This results in 30% abatement in ammonia emissions from trailing hose in comparison to splash plate (Bittman et al., 2014). *Trailing shoe* application reduces the ammonia volatilising surface area by depositing slurry on the soil surface, *underneath* the grass. This results in 60% abatement in ammonia emissions from trailing shoe in comparison to splash plate (Bittman et al., 2014). Some studies suggested that LESS can lead to increased emissions of a potent greenhouse gas, nitrous oxide, however Irish studies on LESS applied to pasture and arable land (Meade et al. 2011; Bourdin et al. 2014) have not confirmed this.

Low emission slurry spreading substantially reduces ammonia emissions, which in turn, has two impacts on N_2O emissions. First, the nitrogen fertiliser replacement value (NFRV) of slurry is increased, reducing the need for fertiliser. Second, the reduction in ammonia results in a reduction in wet and dry deposition of N, which reduces indirect N_2O. The reductions associated with LESS (trailing hose or trailing shoe) manifest in the inventories via a) reductions in mineral fertiliser sales and b) a reduction in atmospheric deposition of N resulting from ammonia emissions.

Emission and uptake assumptions

Only one Pathway was assumed as all slurry from derogation farms must be spread by LESS by 2025. Derogation slurry (26% of slurry) was assumed to be spread by LESS with a 50:50 split between trailing hose and trailing shoe. Of the remaining 74% of slurry, 32.5% was assumed to shift to both trailing hose and trailing shoe respectively. The remainder of slurry was splashplate applied. Linear uptake for non-derogation slurry was assumed. The following ammonia emission factors were utilised for the reference (splashplate) method

Timing of slurry spreading - proportion of total	
Spring	0.52
Summer	0.36
Autumn	0.12
Winter	0.00
Landspreading emission factor (proportion of TAN)	
Slurry-grass	
Summer	0.484
Autumn, winter, spring	0.261

The ammonia emission factors (proportion of N volatilised) for trailing hose and shoe are shown in the table below:

Trailing Hose - Summer EF	0.3391
Trailing Hose - Other EF	0.1826
Trailing Shoe - Summer EF	0.1938
Trailing Shoe - Other EF	0.1043

Cost assumptions

Data from the Teagasc National Farm Survey indicates that 48% of aggregate slurry was applied by contractors in 2018. Slurry can be either contractor spread or farmer spread. The Association of Farm & Forestry Contractors in Ireland (FCI) suggest a rate of €68-€75 per hour for application of slurry by splash plate and €85-€95 per hour by trailing shoe method based on a 11,500 litre tanker. The number of tanker loads that are applied per hour depends on the distance between the tank and the spread lands. In this analysis it is assumed that 3 tankers of slurry per hour are applied using the splash plate method and 2.5 using the LESS methods, as the LESS method tends to be a little slower when applying slurry (Lalor & Schulte 2008, Lalor et al. 2011).

Costs were expressed, relative to the reference (splashplate) method, associated with purchase, maintenance and running of trailing hose and trailing shoe spreaders were calculated (see Table 7.3). These included the annualised differential costs of the purchase of the tanker but also more powerful tractors, upkeep, labour, and fuel costs. The increased nitrogen fertiliser replacement value (NFRV) was netted off the cost. Two cost scenario's were explored – *a high cost scenario*, with fuel price of €1.30 per litre diesel and €2.70 of N fertiliser and *a low cost scenario*, with fuel at €0.53 and N fertiliser at €1.20

Table 7. 3: *List of relative costs (cost model of Lalor 2012) associated with Trailing Hose and Trailing Shoe application of slurry*

		Low Cost		**High Cost**	
From STJ Lalor 2012		**TS**	**TH**	**TS**	**TH**
Ac	sum of annualised capital cost	6302	3588	8721	4829
Ct	capital expenditure (tractor)	14250	9500	14250	9500
Cts	capital expenditure (trailing shoe)	20000	10000	30000	15000
r	interest rate	0.0676	0.0676	0.0876	0.0876
n	loan term	7	7	7	7
Ar	repair cost	3140	1760	4140	2260
rmt	repair cost rate ts/th	0.1	0.1	0.1	0.1
rmts	repair cost rate tractor	0.08	0.08	0.08	0.08
Alab	additional labour cost	1833.3	1833.3	1833.3	1833.3
LSP	labour cost SP	12	12	12	12
LTS	labour cost TS	15	15	15	15
Hsp	Hours worked SP	333.33	333.33	333.33	333.33
Hts	hours worked TS	388.89	388.89	388. 89	388.89
Rsp	slurry application rate SP m3 h-1	30	30	30	30
Rts	slurry application rate TS m^3 h^{-1}	25.714	25.714	25.714	25.714
TS	frac spreading in field	0.25	0.25	0.25	0.25
Wsp	bout width SP	10	10	10	10
Wts	bout width TS	6	6	6	6
Afuel	additional fuel cost	2991.67	2991.67	4916.67	4916.67
Cfuel	cost fuel	0.53	0.53	1.3	1.3
Fp	fuel requirement per kWh	0.3	0.3	0.3	0.3
AnsavTS/TH	Fert saving				
V m3 y-1	Volume spread per year (m^3)	10000	10000	10000	10000
Vcowbeef	av volume hd^{-1}	13.52	13.52	13.52	13.52
Vcowdairy	av volume hd^{-1}	17.16	17.16	17.16	17.16
N	Cost N	1.2	1.2	2.7	2.7
TAN	kg/m3	1.8	1.8	4.05	4.05
	Gross Relative Cost	**14267.12**	**10173.07**	**19611.38**	**13838.78**

Sensitivity Analysis

- *Emissions reduction:* The extent of GHG reduction associated with LESS is relatively small. The main source of variation is the proportion of slurry spread in the summer vs. spring/autumn. If timing is varied between 70%spring/autumn application and 70% summer application, the N_2O emissions reduction varies between 72.1 kT CO_2e yr^{-1} and 131 kT CO_2e yr^{-1}. Only one uptake rate, that 90% of all slurry will be spread using LESS was assessed, due to the fact that; a) derogation farms are already on a pathway towards mandatory LESS usage, b) ever more slurry is being contractor-spread and c) the strong demand for LESS under the TAMS scheme.

- *Costs:* There was considerable sensitivity in the costs associated with LESS. The two most sensitive inputs were a) whether the LESS unit was contractor-owned or farmer owned and b) the amount and price of mineral fertiliser saved. A contractor was assumed to be able to spread, on average, 10,000m^3 of slurry per year, whereas an individual farmer would only spread circa 1,000-1,500m^3 per year. The mean cost per tonne CO_2e abated, if the majority of slurry was contractor spread, across both scenarios was €245±131 $t^{-1}CO_2e$. If every farmer had to buy a LESS unit that cost increased over five-fold to €1145±531 $t^{-1}CO_2e$. In terms of the sensitivity to fertiliser price, it can be observed that under the high cost scenario, despite higher capital and fuel costs er (Table Ax), the increase in the fertiliser price from 1.20 per kgN to 2.70 per kg N resulted in a lower cost per tCO_2e abated compared to the low cost scenario (€140±82.8 $t^{-1}CO_2e$ and €211±108 $t^{-1}CO_2e$ for the high and low cost scenarios respectively).

Inventory and Reporting requirements

Trailing hose and trailing shoe emission factors are already incorporated into the national ammonia inventories (EPA 2021). Activity data in this case is the volume of manure produced by livestock (while housed) and the amount of nitrogen (as total N and ammoniacal N; TAN) in the manure spread in Ireland in spring, summer and autumn. Activity data have been collected by the Teagasc National Farm Survey (Buckley et al. 2020).

Barriers to uptake

The TAMS scheme has proved highly successful, with over one-third of slurry currently spread using low emission techniques. However, there is currently a 10-12 month waiting list for units, a bottleneck that is likely to continue.

In addition, non-derogation farmers who own a splash plate tanker have invested in this technology and may be reluctant/unable to modify this to spread by LESS or may be unwilling to bear the cost of employing a contractor (with LESS equipment) to spread their slurry. This may be especially the case for farmers in low income categories.

Exchequer Costs

The TAMS2 grant for LESS is 40%. Assuming between 2,408 and 4,816 units are required to meet the targets with a 50:50 split – the cost to the exchequer would be between €16.3M and €32.6M.

14. Manure Acidification & Manure Amendments: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	30.2	136	63.5	1.91 to 2.08	25.9 to 28.8	191 to 212
Pathway 2	51.91	244.9	108.3	2.71 to 2.86	35.7 to 39.4	108 to 118
Range	29.7 to 52.6	138 to 245	70.7 to 109	1.93 to 2.86	25.9 to 39.4	108 to 212

See A1.14 for full assumptions and results

The acidification 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. 2011, 2015, Kavanagh et al. 2021, 2022). This is due to the fact that the oxidation of ammonium to ammonia and H^+ is a pH-dependent equilibrium reaction, whereby low pH favours ammonia reduction, while high pH favours ammonium oxidation.

Assumptions

Emissions reduction: It was projected that 10% of slurry (mainly slurry in external stores) was treated with sulphuric or acetic acid, while broiler litter and/or some dairy slurry was treated with ferric chloride, poly-aluminium chloride or alum at the following stoichiometric rates determined from Brennan et al. (2011) alum 1.11:1 (Al: TP); PAC 0.93:1 (Al:TP); $FeCl_2$ 2:1 (Fe:TP).

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).

Uptake: Although this is a mature technology in Denmark, none of the required infrastructure currently exists in Ireland. Therefore both the moderate and enhanced had low uptake rates as follows:

Pathway 1: Dairy, pigs and poultry – 11%, livestock – 8%

Pathway 2: Dairy, pigs and poultry – 20%, livestock 10%

Cost Assumption: The cost of FeCl and alum ranged from €200 – €550 per tonne, while sulphuric acid was costed at €262 per tonne. Annualised costs include a mixer and pump unit to mix in the acid and the cost of safety equipment. The annual costs were estimated at €3562 per annum per unit. Pathway 1 assumed that one-third of dairy slurry and 25% of non-dairy slurry was acidified by 2030, with 50% of pig/poultry slurry acidified by 2030. Under the enhanced reduction pathway, 20% of dairy slurry and 10% of non-dairy slurry was assumed to be acidified by 2030, with 20% of pig/poultry slurry acidified by 2030.

Table 7.4: *Costs Associated with acidification*

Units (Pathway 1)	Units (Pathway 2)	
1800	3600	dairy
6400	8000	beef
24	46	pig
35	70	poultry

	Costs		**Low Cost**	**High Cost**
			Annual cost	
Mixer	6500	7500	**1300**	**1500**
Acidification system maintenance			**500**	**500**
Pump	5000	6000	**1000**	**1200**
Safety equipment	200	200	**100**	**100**
Acid per tonne			**240**	**262**
Total			**3140**	**3562**

Inventory and Reporting requirements

Acidification could be incorporated into national inventories quite easily, particularly if the service was contracted. A percentage reduction of the manure management emission factor for both methane and ammonia could be incorporated into the inventory and in terms of acid introduction would be relatively easy to record, especially as anyone utilising large amounts of acid would require a licence from the EPA.

Barriers to uptake

At between €170 to €212 per tonne CO_2e abated, acidification is a relatively costly measure. The extra NFRV only partially defrays the cost. However, at between 328 kt CO_2e yr^{-1} and 600 kt CO_2e yr^{-1}, it is one of the most effective methane reduction measures. It should be noted that any slurries that are acidified would not be suitable for anaerobic digestion.

Exchequer Costs

There are currently no exchequer costs, although these are likely to be required in order to incentivise uptake.

15. Slurry Aeration: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	58.6	182	91.2	7.98	67.3	396
Pathway 2	89.1	288	148	9.24	95.04	195
Range	58.6 to 89.1	182 to 288	91.2 to 148	7.98 to 9.24	67.3 to 95.04	195 to 396

See A1.15 for full assumptions and results

Slurry aeration reduces methane by oxygenation of slurry which reduces the amount of methanogenesis which requires an anaerobic environment. Studies have shown this reduction to range from 15% to 60% with a mean reduction across studies of 40% (Amon et al. 2006, Viguria et al. 2015, Kresse et al .2009, Mostafa et al. 2019, 2020). However, it can also entail an **increase** in ammonia emissions, depending on how the aeration is performed and the system used for aeration (Amon et al. 2006, Mostafa et al. 2019).

Assumptions

Emissions reduction: It was assumed that methane emissions were reduced by 40% upon aeration with a *20% increase* in ammonia emissions.

Uptake assumptions:

Pathway 1 - Uptake was assumed to be sigmoidal in nature, with 25% of dairy farms and 15% of non-dairy farms employing aeration. A further 25% of pig farms were assumed to employ the system.

Pathway 2 - Uptake was assumed to be sigmoidal in nature, with 40% of dairy farms and 20% of non-dairy farms employing aeration. A further 40% of pig farms were assumed to employ the system.

Cost Assumptions: The cost of an aeration system was estimated at €11,285 per system with the cost annualised over five years with 5% interest rate (low cost) and 7% (high cost). There was also a cost of NFRV foregone costed at €1.20 kg-1N for low cost and €2.70 for high cost scenarios. Defrayed costs was the cost of agitation which was costed at €97 per hour assuming four agitations per year at three hours per agitation.

Inventory and Reporting requirements

Aeration could be incorporated into national inventories quite easily as activity data could be based on the number of units sold. A percentage reduction of the manure management emission factor for both methane and any increase in ammonia could be incorporated into the inventory. The one vital element would be recording the types of aerator as those systems that produce small aeration bubbles (micro-aerators) or sporadic aeration produces lower or little extra ammonia compared to aerators that produce large bubbles and disturbance.

Barriers to uptake

At between €39 and €46 per tonne CO_2e abated, aeration is a relatively cost-effective measure, with labour being the major cost saving. It is also advantageous as the slurry remains usable for biomethane production. The big issue is the potential loss in NFRV and ammonia loss. However, used in conjunction with a small amount of acidification from adding in silage effluent, could counteract the ammonia loss while maintaining the slurry as an effective feedstock for anaerobic digestion.

Potential Exchequer Cost

If the exchequer were to grant-aid these systems in line with LESS, this would entail a 40% defraying of cost to the farmer. Cost to the exchequer would thus be €11.2M to €22.4M

16. Drainage of wet mineral soils and reduction in soil compaction: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	57.0	145	74.2	-19.7 to 23.1	-49.2 to 57.8	-339 to +399
Pathway 2	128	363	163	-40.0 to 2.74	-100 to +6.86	-276 to +18.93
Range	57.0 to 128	145 to 363	74.2 to 198	-40 to 23.1	-100 to +57.8	-339 to +399

See A1.16 for full assumptions and results

Drainage of wet mineral soils was calculated to be based on a reduction in the nitrous oxide emission factor. According to data from the Irish Soil Information System (SIS), one-third of Irish land area can be classified as poorly draining or prone to compaction.

Emissions and Uptake Assumptions

This change in emission factor was based on modelled outputs using the DeNitrification Decomposition model (Li et al. 2012) and validated based on the range of emission factors generated by Harty et a. (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}.

Cost Assumptions

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 20m apart and deep drains at 30m apart with subsoiling. When costs for re-seeding, fuel and labour were included, this resulted in total costs of €2,250 per hectare. Assuming a baseline dairy and beef farm grass growth rate of 10 tonnes ha^{-1} and 8 tonnes ha^{-1} respectively, a 20% increase in grass growth post-drainage and an increase in profitability of €181 ha^{-1} and €105 ha^{-1} (Teagasc 2020).

Sensitivity Analysis

Drainage was very cost sensitive to a) use of gravel moles versus shallow moles (costs ranging from 125 – 1400 euro per ha), b) frequency/spacing of collector drains (between 800 and 3,200 euro per ha based on 60m and 20m spacing respectively) and 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.

Inventory Inclusion

This measure will require spatially explicit soil type x drainage status activity data. Fertiliser and dung/urine emission factors were developed for free-, medium- and poorly-drained soils (Harty et al. 2016, Krol et al. 2016), but there is a lack of spatial soils data. This measure will therefore require land parcel level reporting.

Barriers to Uptake

The main barriers to uptake are mainly cost related. In addition, con-acre is unlikely to be drained. Also, there may develop confusion between the twin messages of draining **mineral** soils while simultaneously advocating rewetting of **organic** soils and possibly organo-mineral soils in future.

Exchequer Costs

Land drainage in ineligible for grant aid and this is likely to remain.

17. Use of digestate or bio-based fertiliser in place of slurry: Absolute emissions reduction

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	3.81	64.14	18.19	-0.024 to -0.218	+0.406 to -1.92	+6.34 to -29.93
Pathway 2	19.93	335	95.04	0.423 to 0.971	-9.99 to -24.9	-74.2 to -24.9
Range	3.81 to 19.93	64.14 to 335	18.19 to 95.04	0.97 to -0.218	+0.41 to -24.9	-1.36 to -73.1

See A1.17 for full assumptions and results

This measure exploits uptake of measure 29 Biomethane. A consequence of this measure is the production of large amounts of digestate. This digestate differs from conventional animal slurries in that all of the nitrogen is plant-available. In addition, the digestion process utilises volatile solids in in slurries and other co-digestion substrates (eg. Grass) which results in the remaining carbon content of digestate being more recalcitrant.

Emissions and Uptake Assumptions

In terms of biomethane, Pathway 1 has 50 plants producing 1. TWh of gas, while Pathway 2 has 285 plants producing 5.7 TWh. The feedstock is 20.8kt fresh weight silage and 14 kt slurry. Pathway 1 requires 520,000 m^3 of slurry while Pathway 2 requires 3.5 million m^3 slurry. The volumes was assumed to be 50% bovine and 50% pig slurry. This would result in Pathway 1 consuming 1.95% and 9.76% of all bovine and porcine slurry, while Pathway 2 would consume 8.2% and 40% of all bovine and porcine slurry. As this slurry is placed in a gas-tight digester, there was a reduction in methane and N_2O emissions during the storage period of 59 $ktCO_2e\ yr^{-1}$ and 244 $ktCO_2e\ yr^{-1}$. However, there are also fugitive emissions associated with methane leaking from digesters and this was assumed to be 0.6% of all methane produced (Balde 2022). This reduced the net GHG storage savings to 50.4 and 207 $ktCO_2e\ yr^{-1}$ for both pathways. In addition, the nitrogen fertiliser replacement value (NFRV) of digestate is higher than that of raw slurry. The moderate and enhanced pathways would produce 188 kt and 700kt digestate. This would displace 615 and 2522 tonnes N, resulting in a net N_2O saving of 23.9 $ktCO_2e\ yr^{-1}$ (moderate pathway) and 97.9 $ktCO_2e\ yr^{-1}$ (enhanced pathway). Therefore the total emissions savings accruing to agriculture would be 83.5 $ktCO_2e\ yr^{-1}$ (Pathway 1) and 342 $ktCO_2e\ yr^{-1}$ (Pathway 2).

Cost assumptions

All digestate would need to be either processed (dewatered) to produce a bio-fertiliser or acidified, in order to prevent large ammonia emissions upon land-spreading. The low and high cost scenarios assumed that the cost of acidification/processing was €4.44 and €6.44 per m^3

digestate (see acidification measure). N savings were estimated at €1.20 and €2.70 per kgN. Total net costs were 0.23 and 8.4 million for the low and high cost scenarios resulting in a cost per tCO_2e of €-24.90 and €-348 for the low and high cost pathway respectively.

Sensitivity analysis

Emissions: The main sensitivity of the measure is the fugitive emissions associated with biogas and biomethane facilities. An increase in fugitive methane from 0.6% to 2% would halve the mitigation potential of storage emissions as the fugitive emissions would increase from 37.5 $tCO_2e\ yr^{-1}$ to 125 $tCO_2e\ yr^{-1}$. The other main source of uncertainty is the level of biomethane that will occur. The range of 1 to 5.7 TWh covers the range of targets from SEAI (2017) enhanced biomethane target to the new national biomethane target.

Incorporation into inventories

The reduction in slurry emissions from storage can be accounted in inventories. Activity data in terms of the volumes of slurry being utilised in biogas/biomethane facilities would be required. Also fugitive emissions associated with the biogas facilities would need to be characterised. In terms of N_2O emissions from landspreading of digestate, the current default EF1 of 1% is used in the calculation and a digestate specific EF_1 would need to be quantified (this is currently under investigation in the DAFM-funded LAB-MACC project) and the volume of digestate being returned to land would need to be recorded.

Barriers to uptake

The main barrier to uptake is the establishment of a viable scaled up biomethane sector. In addition, the treatment or processing of digestate would require associated processing facilities adjacent to the biogas facility. In particular, there is a danger that untreated digestate could substantially increase ammonia (and hence indirect N_2O) emissions. This could be mitigated through the use of LESS and acidification.

Exchequer Cost

Potential cost to the exchequer is calculated in Measure 29

18. Diversification Impacts on Livestock Numbers

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	79.3	150	90.9	-2.40	-4.5	-30.27
Pathway 2	235	417	248	-6.22	-11.15	-26.73
Range	79.3 to 235	150 to 417	90.9 to 248	-2.40 to -6.22	-4.5 to -11.15	-26.73 to -30.27

See Tables A1.18 for details and assumptions

Farm diversification refers to the practice of expanding the range of products and services offered by a farm beyond traditional agricultural crops or livestock. The goal of farm diversification is to increase the profitability and sustainability of a farm by reducing dependence on a single commodity or market, and by creating new revenue streams. It can also help to build stronger connections with local communities and consumers, and to increase the resilience of a farm against external economic or environmental challenges.

In this study, we examined the following

- Conversion of conventional farms to organic production systems
- Afforestation
- Use of grass as feedstock for biomethane
- Increase in tillage area

Uptake assumptions

Pathway 1: 3.75% uptake of organic systems, 8kha forestry and 50kha required, 30 kha grassland for biomethane, 20 kha of tillage expansion

Pathway 2: 7.5% uptake of organic systems, 8 kha forestry, 120kha of grassland for biomethane, 30kha of tillage expansion

Principally beef rearing, beef finishing and sheep systems were displaced, and these farms comprised the lower 25th percentile from National Farm Survey (Dillon et al. 2022).

Emissions Assumptions

It was assumed that organic stocking rates reduced by only 12% as the stocking rates on these farms would be low (circa 1 LU ha^{-1}) already. In terms of tillage, biomethane and forestry, a 50% reduction in stocking rate was assumed. No fertiliser impact was assumed as this was already addressed in the 'Clover and Multi-species sward' measure.

Cost Assumptions

Farm costs and income were derived from Dillon et al. 2021. Farm subsidies were still assumed to remain constant, with only income and expenditure from livestock rearing/finishing impacted.

Inventory incorporation

Farm diversification impacted on bovine and ovine number and so is fully incorporated into the national inventory.

Barriers to uptake

The main barrier for uptake is social and cultural. Shifting farm enterprise is difficult and farm diversification can be a challenging process that requires careful planning, research, and investment. However, it can also offer many benefits to farmers and rural communities, including increased economic opportunities, improved sustainability, and enhanced cultural and environmental stewardship.

Exchequer costs

Exchequer costs for biomethane are covered in Measure 30 and for forestry in Measures 19-23. A budget of €256M has been allocated for organic farming over the next four years (2023 to 2027).

7.2. LULUCF Measures

7.2.1. Forestry measures

Measure	2030 Mitigation	Mean $ktCO_2e$	€ t^{-1} CO_2e	Total cost	Mean $ktCO_2e$	€ t^{-1} CO_2e	Total cost
Pathway 1							
Extend rotation 21%	387	560	-88	-49,280,000	9.6	-88	-847,407
Avoid deforestation	140	140	13.1	1834000	156.4	13.1	2048452
Agroforestry	7.4	3.4	240	576000	24.1	40.2	969267
Afforestation	278	90	236	19,512,639	955.8	60.43	57,757,893
NWC (Raised bogs)	-2	20	237	3200000	198.2	10.92	2164182
Pathway 2							
Extend rotation 31%	890	873	-130	-113490000	14.9	130	-1937000
Avoid deforestation	140	140	13.1	1834000	156.4	13.1	2048840
Agroforestry	14.8	7.8	240	1872000	48.2	83.14	4007348
Afforestation	278	90	236	21240000	1272	107.23	136396560
NWC (Raised bogs)	-2	20	237	4740000	198.2	16.17	2164182

See Appendix 2 for assumptions

Forest and harvested wood product (HWP) sinks have made a significant contribution to offsetting net emissions from Ireland's LULUCF sector in the past (EPA, 2022). However, the forest contribution has been declining in recent years (EPA, 2022) and is projected to transition from a net sink to a net source by 2035 (Black et al., 2012; NFAP, 2020). This transition is associated with a substantial reduction in the level of afforestation, over the past 10 years, which has resulted in lower levels of additionality, especially as young trees have limited capacity to sequester carbon in the early years. An increase in the level of harvest from the private sector combined with the unbalanced age profile of forest growing stock are likely to result in net emissions from the harvested wood sector. Recent changes to the emissions profile of organic soils in forests as a result of newly published emission factors and a decline in growth rates associated with age class legacy shifts have all contributed to changes to the forest carbon sink(EPA, 2022; NFAP, 2019, Black et al., 2022, 2012). Despite recognition that certain forest management options can have a low marginal abatement cost and high short-term potential to reduce net emissions in Ireland (Black et al., 2022) and across the EU (EC, 2021), there has been relatively little modelling of specific management options. Wood harvests are projected to almost double from over 4Mm^3 per year to over 7.9 Mm^3 by

2035 (COFORD, 2021), and incentives to keep wood in forests for longer, where deemed appropriate, could certainly delay and mitigate the imminent “carbon cliff” in forest carbon stocks projected under business-as-usual. This could play an important role in determining the emission ceiling achievable by LULUCF sector under the Climate Action and Low Carbon Development (Amendment) Bill and how the proposed EU LULUCF targets for 2030 can be met. While many crops in Ireland are currently harvested early, owing to market demand and buoyant positive timber prices and owner time preferences, the option of delaying harvest in suitable forests to a time when biomass production reaches a maximum (age of maximum mean volume increment – AMMAI) merits analysis. However, growing forests over longer time frames are not without challenges, and have implications for expected future wood harvests and timber supply, delays in income streams for forest owners and an increase in the average tree size. Opportunities to adjust rotation length may result in greater risks of windthrow and may be limited to soils with good drainage and more limited on soils where stability is a known issue such as wet mineral soils in Ireland.

Scope and system boundary

Projections were run for the period 2021-2050 based on the reporting and accounting framework specified in the EU LULUCF (2018) regulation, where GHG profiles are reported in three categories:

- Afforestation of land (AR) up to 30 years of age;
- Managed forest land (MFL) includes all second rotation crops and transitioning afforestation areas, which are older than 30-year old;
- Deforested land (D) included all forest land which is converted to another land use.

GHG profiles for each of the three categories include all of the 6 pools specified in the EU LULUCF regulation.

- Aboveground biomass
- Belowground biomass
- Litter
- Deadwood
- Mineral and organic soils
- Harvested wood product

There is no evidence of livestock displacement due to afforestation (see EPA, 2022). Therefore, emissions reductions associated with livestock displacement are not included. In the case of deforestation, however, 43% of deforestation occurs in grasslands where dairy is assumed to be the agricultural activity. Emissions associated with dairy farming on deforested land is included in the system boundary.

Assumptions and approach

Model description

The Carbon Budget Model, developed by the Canadian forest service (CBM-CFS), was used for modelling greenhouse gas (GHG) profiles of the national estate. CBM-CFS is a carbon modelling framework for stand and landscape level forest ecosystems. It has been under development by the Canadian Forest Service for over 20 years and is compliant with the requirements under the International Panel for Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change and Forestry. There are numerous examples of its use globally (Kurz et al., 2009), including in Canada, at European scale by the European Commissions' Joint Research Centre (Pilli et al, 2018) the Czech republic, Poland and in Ireland (EPA, 2022, Black et al., 2022).

The forecast scenarios were based on CBM simulations using target harvests and silvicultural rules obtained from the timber output scenarios. The model was calibrated for Ireland based on NFI data and silvicultural rules (Table 4.7) defined in the last all Ireland roundwood forecast (COFORD, 2021). A key feature of the model is that it can dynamically simulates the landscape effects of forest management and disturbances. In particular, the model allows specification of the age class structure and changes in silviculture to evaluate different climate change abatement options at the stand and landscape level.

A full description of the calibration and validation of the CBM_CFS model for Irish forestry is presented in the Irish Greenhouse gas inventory report (EPA, 2022), the Irish national forest accounting plan (NFAP, 2020) and recent modelling work done for the Coillte estate (Black et al., 2022).

Removals and emissions from the harvested wood product (HWP) pool was estimated using the IPCC inflow and exponential decay method with inflow and decay functions for Ireland (EPA, 2022, Black et al., 2022).

Measure 19. Afforestation

The age class structure and species-productivity for given soil types was derived for the existing afforestation areas (1990-2021) from the NFI sample based inventory in 2021 (NFI, 2021). In order to simulate the GHG profiles for afforestation lands over the period 2021-2050, the model utilised two different approaches:

The 30-year transitions of existing afforestation areas (1990-2021) were simulated using CBM-CFS and this transitioned to managed forest land (MFL) after 30 years. The remaining areas are added to the scaled-up estimates (see point b).

The afforestation scenarios from 2021 onwards based on a 30-year transition were based on standardised volume curves developed using GROWFOR (Broad and Lynch, 2006). The CBM model then converts volume to biomass components and carbon (C) curves were generated for different forest types (Table 7.5). These C lookup curves were then be used to scale up to a national level based on user-defined inputs such as annual afforestation scenarios, proportion of species and site indices based on varying proportions of 3 major soil categories (i.e. mineral, mineral-organic and organic).

Table 7. 5: *Species strata and silvicultural assumptions used for afforestation and forest management from 2023*

Strata Details				Harvest Assumptions					
Strata Code	**Species**	**YM Sp.**	**YC**	**Thin**	**1st thin age**	**Number of Thins**	**Thin Cycle**	**Rotation Age**	**NFAP Rotation Age**
FGB	Birch, ash, ald, syc	Ash	10	Thin	15	4	5	35	38
SGB	Oak, beech	Oak	6	Thin	25	13	5	90	65
OC	Other conifers	DF	18	Thin	18	4	5	36	40
PineYC8NT	LP/SP	LPSC	8	No thin	-	-	-	46	46
PineYC10NT	LP/SP	LPSC	10	No thin	-	-	-	42	42
PineYC14	LP/SP	LPSC	14	Thin	20	3	4	44	
SpruceYC8NT	SS/NS	SS	8	No thin	-	-	-	50	50
SpruceYC12NT	SS/NS	SS	12	No thin	-	-	-	42	39
SpruceYC16NT	SS/NS	SS	16	No thin	-	-	-	37	34
SpruceYC20NT	SS/NS	SS	20	No thin	-	-	-	32	31
SpruceYC24NT	SS/NS	SS	24	No thin	-	-	-	30	27
SpruceYC28NT	SS/NS	SS	28	No thin	-	-	-	27	
SpruceYC16	SS/NS	SS	16	Thin	22	2	4	37	34
SpruceYC20	SS/NS	SS	20	Thin	20	2	4	32	31
SpruceYC24	SS/NS	SS	24	Thin	18	2	4	30	27
SpruceYC28	SS/NS	SS	28	Thin	16	2	4	27	

Future afforestation assumptions are based on the Climate Action Plan assumptions of 4,500 ha per year from 2023-2025, ramping up to 8,000ha per year for the period 2026 to 2030 and followed by a decline to 4,000 ha per year from 2031 to 2050. Afforested soil types are assumed to be based on current afforestation trends using the 2021 NFI data. Future afforestation is assumed not to occur on raised bogs or blanket peats (unenclosed land) but some organic soils (13%) may be afforested if previously used for agriculture. Organo-mineral soil and mineral soils were assumed to represent 11 and 76% of afforested areas in the future.

The percentage of different species assumed for future afforestation is shown in Table 7.6.

*Table 7. 6***:** *Percentage of species and silvicultural strata assumed to represent future afforestation.*

Strata Code	% of area
FGBYC4	14.00%
FGBYC10	14.00%
SGBYC4	7.00%
SGBYC6	7.00%
OC	0.00%
PineYC8NT	0.00%
PineYC10NT	0.00%
PineYC14	3.00%
SpruceYC8NT	2.00%
SpruceYC12NT	2.50%
SpruceYC16NT	2.50%
SpruceYC20NT	8.00%
SpruceYC24NT	8.00%
SpruceYC28NT	1.00%
SpruceYC16	7.00%
SpruceYC20	6.00%
SpruceYC24	10.00%
SpruceYC28	8.00%
Sum	100.00%

Table 7.7 below presents the percentage of the strata that will be thinned. The percentage of thinning in the for the higher yield class spruce strata of 64% is from the 2021 roundwood forecast questionnaire which asked forest managers in the private sector the percentage of forests to be thinned. The 60% for the FGB and SGB is also a result from the 2021 Forecast questionnaire (COFORD., 2021).

Table 7. 7: Species strata thinning percentages

Strata	Thin	No thin	LTR
FGB	60	20	20
SGB	60	20	20
OC	64	31	5
PineYC8	0	40	60
PineYC10	0	60	40
PineYC14	0	80	20
SpruceYC8	0	40	60
SpruceYC12	0	60	40
SpruceYC16	50	40	10
SpruceYC20	64	26	10
SpruceYC24	64	31	5
SpruceYC28	64	36	0

HWP inflow assumptions are as follows:

- All pulp and pallet from FGB and SGB are used for firewood
- 1st thinning pulp from spruce used for fire wood
- All other assortments applied to HWP
- Fossil fuel displacement is not considered since this is reported under the energy sector.

Abatement cost

The abatement cost for afforestation was based on the annuity method which derives the annualised discounted cashflows from the new afforestation grant and premiums, projected timber revenues and projected CO_2 sequestration rates for the period 2023 to 2030 and 2023-2050. A discount rate of 5% is used for all calculations. Timber volumes and revenues were derived using GROWFOR (Broad and Lynch, 2006) based the long-term volume price curves. The cashflow and CO_2 sequestration rates were based on the most representative forest types used for afforestation, 70% Sitka spruce YC 20 (50% of which were thinned) and 30% YC 6 Ash. The same silvicultural assumptions shown in tables 1 and 2 were used.

Measure 20. Avoidance of deforestation

The current level of deforestation is 752 ha per year over the period 1990-2021 (EPA, 2022). Deforestation was applied to all MFL scenarios assuming a future deforestation rate of 495 ha per year.

The measure of avoiding deforestation assumed an annual rate of 495 ha per year over the period 2023-2050. Deforestation emissions were based on the GHG inventory median deforestation emission of 263 tCO_2 per ha for the period 1990-2021 (EPA 2022). Emissions from livestock associated with grassland conversions is based on the average value per ha for dairy farms (9tCO_2 per ha per year, (Buckley et al. 2022)). It is assumed that the current average of 43% of deforested lands are converted to dairy pastures.

Abatement cost

The abatement cost of avoidance of deforestation (13 € per tCO_2) was based on a replanting cost of 3500 €/ha and the mean annual deforestation emission of 266.8 tCO_2 eq. per ha.

Managed forest land

All MFL projections were derived from CBM-CFS simulations using the approach reported for Ireland's NFAP (2020). Emissions from organic soils are based on new emission factors now used in the national greenhouse gas inventory (Duffy et al., 2022).

BAU scenario

Additional measures related to forest management are derived as the difference in emissions or removals relative to a business as usual (BAU**)** baseline. The BAU scenario uses the same silvicultural assumptions applied in the roundwood forecast (COFORD, 2021). The baseline harvest scenario is the same as used for the FRL (NFAP, 2020) under the EU LULUCF regulation (i.e. a harvest to increment ratio of ca 70% and the target harvest from the 2018 roundwood harvest). The species-productivity-soil matrix and age class strata are identical to the NFAP (2020).

Measure 21. Adjusted rotation

Current management practice of conifer forests adopts a rotation age, which is somewhere between 30 to 40% less than AMMAI (the age at maximum mean annual timber volume increment) for spruce and pine crops based on market demand. This means that crops are currently harvested before maximum productivity is reached. This practice results in a lower peak CO_2 sequestration (Black et al., 2022) and a loss of timber revenues, when compared to the conventional rotations to AMMAI with a static timber price. Retention of forests closer to optimum productivity or transformation of forests into longer term silvicultural systems such as continuous cover forestry (CCF) are silvicultural pathways which can be used to maintain biomass in forests for the longer term, thus reducing emissions in the shorter term. The practice of reducing the rotation age has an additional impact at the landscape level as it speeds up the age class shift effect on productivity, which has been shown to reduce sequestration potential in MFL (Black at al 2021). The overall impact is that the transition of MFL from a net removal to a net emission (i.e. the "carbon cliff") will occur at a point sooner in time (See Figure 1).

Recent analysis has indicated that adjusting therotation age to AMMAI has been shown to increase CO_2 sequestration in the Coillte estate (Black et al., 2022). However, adjusting the rotation age in some cases may not be practical owing to concerns about windthrow and other silvicultural constraints so its applicability to the national estate may be limited. Adjusting rotation ageincluding transformation to CCF measures where appropriate, can represent apathway to reduce emissions from MFL. However, the implications of such a pathway for forest owners and the wider forest sector, including for timber availability/log processing sizes and potential impacts on motivations for forest establishment and management requires full consideration and analysis.

It has been estimated that approximately 21% to 31% of the area within productive conifer crops in the national forest estate may be deemed technically suitable for longer term retention or for CCF implementation. This is based on the likely risk of windthrow as modelled with the windthrow risk model which was applied to NFI data and used in the P1 scenario. However, the growth models for CCF are still being developed and validated (COFORD-funded Continufor project). It is assumed that introduction of CCF would have the same short-term landscape impact as arotation to AMMAI. Another scenario, pathway 2, utilised a higher percentage (31%) of the area of conifer crops, which may be technically suitable for longer term retention/CCF in the analysis.

Abatement costs

The annuity methods were applied using timber revenues from the year the extension of rotation was implemented for a Sitka spruce crop with a growth rate of yield class 20 under 70% MTI. The rotation age was increased from 32 to 38 years. Timber volumes and revenues were derived using the GROWFOR growth model for Sitka spruce. Additional operational and management costs (mean of 108€ per ha) were applied to the longer term rotation scenario. The extension of rotation results in a discounted profit of 2,182 € ha^{-1} and an additional 24.6 tCO_2 per ha is sequestered. Therefore, the cost abatement for extension of rotation is negative (-88€ per tCO_2). However owner time preferences for income have not been factored in to this calculation and incentivising owners to retain their crop will have an associated cost should they choose this option.

Measure 22. Woodland conversion in raised bogs

The carbon balance of afforested stands on peatland sites is initially a net removal but there is a reported gradual transition to a net emission after 1-3 rotations (Hargreaves et al., 2003, Black et al., 2022). A key climate change abatement strategy is to reduce emissions associated with clear felling or intensive management. Encroachment of birch in low yielding conifer stands on afforested raised bog sites is quite common, particularly in the cutaway bogs (Black et al., 2017). In addition, there are native woodland conservation grants available to incentivise replacement of conifer crops with native woodlands such as birch woodlands. Analysis of Coillte and NFI data suggest that approximately 20,000 ha of planted conifer forests are currently or have the potential to be encroached by birch and willow. For this scenario, 17,920 ha of yield class 4 to 12 Sitka spruce, Norway spruce and Lodgepole pine was converted to birch woodland. In order to reduce disturbance emissions associated with clear-felling the conifer crops, stands were intensively thinned to waste (75% of the area) at year 25. Birch is assumed to be introduced by natural regeneration or by planting coupes within the existing stands. The broadleaf areas are assumed to be retained for biodiversity only.

Abatement cost

The abatement cost of woodland conversion in raised bogs (NWC raised bogs) was based on the current NWS conversion grant and premium rates applied to 17,920 ha over the period 2023 to 2050. The total discounted cost for this scenario is 31.5M€ for the period 2023-2030 and 51.4 M€ for the period 2023-2050. The total reduction in emissions from MFL (Table A3 in appendix) was 0.19 and 5.4 $MtCO_2$ for the period 2023-2030 and 2023 to 2050, respectively. Therefore, the derived abatement cost is higher in the short term (166€ per tCO2 for 2023-2030), compared to long term costs (10.95€ per tCO_2 for 2023-2050).

Measure 23. Agroforestry

Agroforestry models for GHG balances are taken from the Forest Carbon Tool work done for Teagasc. It is assumed that afforestation of agroforestry will be 125ha per year from 2023 to 2030, doubling to 250 ha per year from 2031-2040 and to 500 ha per year for 2041-2050. The afforestation rates are assumed to be additional to the climate action plan target.
For the agroforestry scenarios, volume increment curves were based on single tree DBH and height increment models for Oak and Sycamore (Cabanettes et al., 1999) assuming and initial stocking of 400 tree/ha at a spacing of 5m. The oak model was developed for agroforestry in France using *Q. rubra*, so the growth curve was adjusted for Irish conditions by ensuring the DBH at age 30 was 17cm. This is 1.6 times the DBH of 30-year-old oak when grown in plantations (BFC YC 8 oak). Cabanettes et al. (1999) reported that the DBH of open grown *Q. rubra* is ca. 1.6 times that of plantation grown oak. The growth curve for sycamore was based on data from Scotland (Cabanettes et al., 1999). This model agrees well with an AFBI ash agroforestry experimental plot data in Loughgall (Northern Ireland). Tree volume was derived using the single tree stem profile model for Ash (NFI, 2017). Thinning's were assumed to be based on a crown thinning where crown areas of trees are maintained to ensure no overlap or crown competition so that free growth is maintained. Crown radius was calculated using the equations developed by (Pretzsch et al., 2015). Crown thinnings took place when the crown radius ratio was just below 1 and stocking was reduced to a crown radius ratio of 0.8 after thinning. The crown radius ratio was calculated as quotient of the crown radius over half the distance between trees, where the distance between trees increases as thinning interventions take place. The rotation age for agroforestry systems was based on a DBH target threshold of 60cm (Short pers. comm.). The stand volume increment equations and target harvests for the agroforestry systems were incorporated into CBM-CFS for estimation of forest C sequestration rates. The two rates of agroforestry were 1,000 ha and 2,000 ha by 2030 for Pathways 1 and 2. By 2050, the rates of agroforestry in the analysis are increased to8,500 ha and 17,000 ha for Pathways 1 and 2 respectively.

Modelling of carbon fluxes for agroforestry is based on limited but the best data available data to date. Additional growth data and models will be incorporated as they become available to enhance future analysis.atement cost

The abatement cost for agroforestry was based on the annuity methods, as used for afforestation. The current grant and premium revenues were used to calculate the annualised cost. No revenues are assumed to come from timber sale over the analysis period in question.

Results

Historic and future BAU trends

The historic, current and future GHG emission/removal profiles of afforestation (L-FL), forest management (MFL, Figure 1) and the total forest area (Figure 7.3) show that GHG fluxes are primarily driven by the level of harvest. The increase in removals from afforested land (L-FL, Figure 1) from 1990 to 2020 is also associated with the higher levels of afforestation in the mid-1990s. Removals in this category increased to over -3,000 Gg CO_2 per year by 2020 due to increase growth but there has been a decline in net removals in recent years due to an increase in harvest since 2018 (Figure 7.3). This level of harvest is expected to increase 4-fold by 2031 where afforested lands are predicted to be a net emission of 30 GgCO_2 per year. This trend is also driven by the reduction in afforestation rates from over 25,000 ha per year in the mid-1990s to the current rate of approximately 2,000 ha per year. The afforestation trend is expected to reverse after 2031 due to the higher assumed afforestation rates under the climate change action plan. An afforestation rate of 4,500ha is assumed from 2023 to 2025, 8,000ha per annum is assumed from 2026 to 2030 and from 2031 to 2050 a rate of 4,000ha is assumed.

Another feature of afforested land is that most afforestation took place on organic soils in the 1990s and when these areas are transitioned to the MFL category, they are harvested where they become a net emission due to continued emission from organic soils. The MFL level of harvest is also expected to increase from 3 Mm^3 in 2020 to over 7 Mm^3 by 2036. The increase in current and future harvest rates (Figure 7.3 and 7.4), will be derived from the private estate (COFORD, 2021) and this is the major driver of the predicted increase in emissions for the MFL category (Figure 7.3) and the total forest estate (Figure 7.4). Although the level of harvest in the Coillte estate is predicted to stay relatively stable at ca. 2.2 Mm^3 per year, the GHG profile of the Coillte estate is also predicted to transition to a net emission by 2040 due to continued emissions form organic soils and age class structure shifts (Black et al., 2012; 2022)

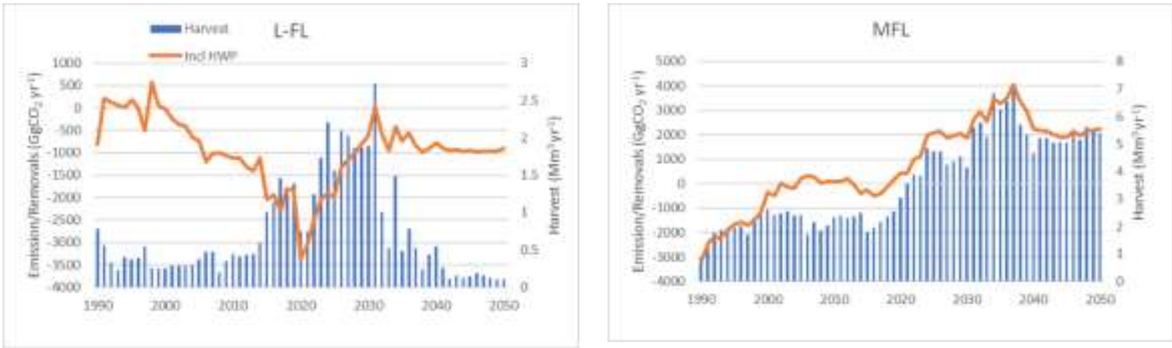

Figure 7.3: *Historic and projected future GHG profiles (including HWP) of afforested (L-FL) and manged forest land (MFL) categories. Future GHG trends assume business as usual scenario for the period 2023-2050. Negative values represent a net removal, positive values are a net emission.*

The combined influence of a decline in afforestation, continued emissions from organic soils, a 7-fold increase in the level of harvest since 1990, and a reduction in landscape level productivity due to age class structure shifts (Black et al, 2012) has resulted in a dramatic shift from a net removal of -4,000 $GgCO_2$ per year in 1990 to a net emission of 3,000 $GgCO_2$ per year by 3036 (Figure 7.4).

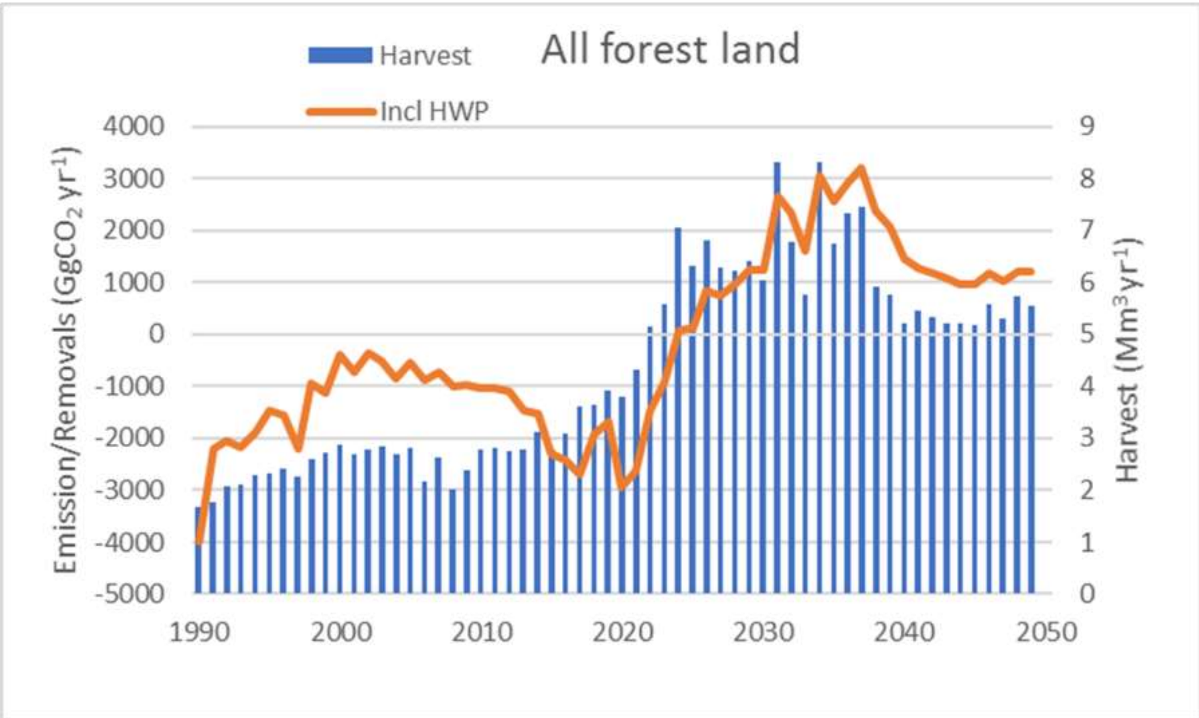

Figure 7.4: Historic and projected future GHG profiles (including HWP) of all forest land categories. Future GHG trends assume business as usual scenario for the period 2023-2050. Negative values represent a net removal and positive values are a net emission.

7.2.2. Afforestation measures

In the absence of future afforestation, the GHG profile of the existing afforested lands will be a net removal of -15,731 $GgCO_2$ for the periods 2021-2030. This declines to a net emission of 715 $GgCO_2$ in the long term (2031-2050) due to increasing net emissions from 2040 onwards.

Additional removals due to assumed afforestation rates under the climate change action plan is projected to be -761 $GgCO_2$ for the period 2021-2030.

Figure 7.5: *Net forest and HWP removals/emissions from existing and future afforestation assuming annual afforestation rates of 0 (i.e. no additional afforestation from 2021) and the climate change action plan assumptions of 4500-8000 ha per year for the period 2023-2030. Long-term afforestation rates of 4000 ha per year are assume for 2031-2050.*

The potential contribution of afforestation towards meeting short term targets (2021-2030) is quite small because of the initial slow growth of forests and initial emissions from organic and organo-mineral soils (Figure 7.5). The additional afforestation impact increases significantly in the longer term, where total removals over the period 2021 to 2050 is 25,806 kt CO_2e or 25.8 Mt CO_2e (Figure 7.5).

Managed forest land scenarios

Adjusted rotation

Adjusting rotation age to MMAI in 21% or 31% (77,673 ha or 114.660) of commercial plantation areas would result in an initial reduction in emissions of 4,479 GgCO2, relative to the BAU scenario, for the period 2023-2030 (Figure 4.4). However, for the entire period 2023-2050, this measure would result in a decrease in emissions 226 GgCO2 (Figure 7.6). An adjustment to the forest rotation scenario to retain the forest in situ for longer in effect delays the "carbon cliff" because there is a higher harvest volume when the rotation adjustment age threshold is met.

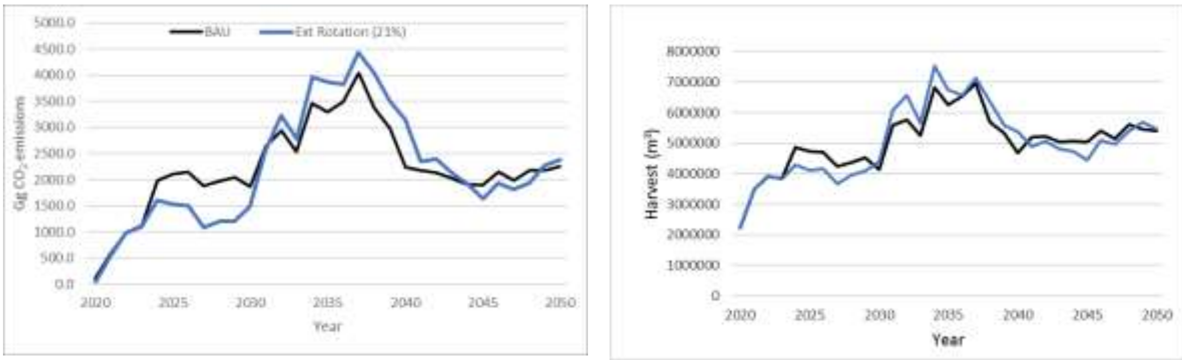

*Figure 7.6**:** Net GHG emission/removal and harvest profiles for the extended rotation (Ext. rotation) and business as usual scenario (BAU) scenarios.*

The adjusted rotation scenario would have significant commercial implications for timber production. The average level of harvest will reduce by 0.25 Mm^3 per year (a total of 2.5Mm^3) for the period 2023-2030, when compared to the BAU scenario which is based on the all-Ireland roundwood forecast (Figure 4.4). However, the level of harvest under the adjusted rotation scenario would be maintained at the current rate of 4Mm^3 per year up to 2030. The level of harvest for adjusted rotations then exceeds the BAU rate for the period 2031-2043. The overall impact on harvest over the long term is a slight increase in harvest of 0.09Mm^3 over the period 2023-2050.

The adjusted rotation scenario would also have other significant potential effects across the sector, including in relation to timing /extent of income streams for forest owners and in relation to potential adjustments to realisable timber volumes and relative product sizes over the period in question. With regard to potential implementation of this pathway option, a suitable facilitative structure would be also required to ensure positive outlook among landowners /existing forest owners in relation to future forestry uptake and appropriate forest management preferences. Implementation of the adjusted rotation option should therefore be informed by a full socio-economic analysis of proposed scenarios and consultation with relevant stakeholders.

Natural woodland succession on raised bogs

The use of natural succession and conversion to low intensity woodland management of 17,920 ha of forests deemed to be more suited to natural processes could be utilised. This would allow natural processes to evolve in which these forests revert toto mixed and/or-broadleaf woodlands over the period 2023-2050. This would result in a reduction in 5,351 $GgCO_2$ emissions, when compared to the BAU scenario (Figure 7.7). Short-term emission reductions are modest (197 $GgCO_2$ for 2023-2030). The reduction in emissions are associated with improved growth increment in mixed forests more suited to these site types relative to underperforming commercial crops and more limited management which results in the retention of carbon for longer time periods on these crop types. The slight reduction in harvest from 2040 onwards, relative to the BAU harvest also has a small impact on the GHG profile.

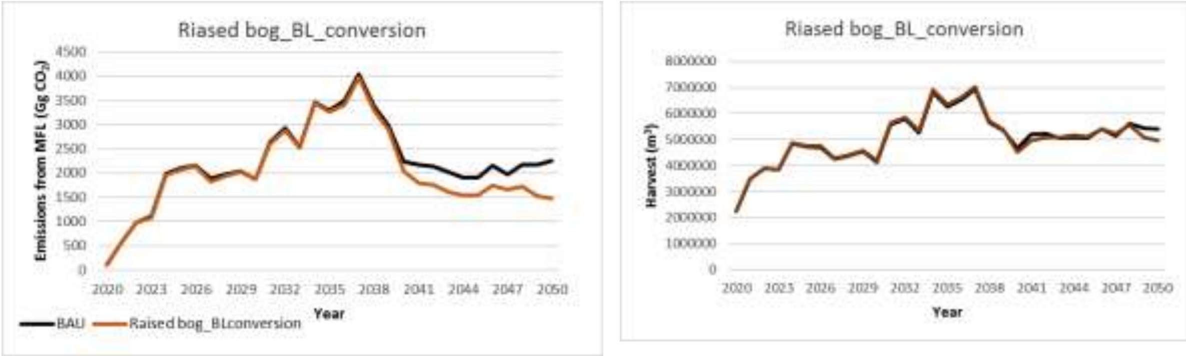

Figure 7. 7: Net GHG emissions for the Raised bog broadleaf conversion and the BAU scenarios in MFL over the period 2020-2050.

Additional agroforestry

Additional afforestation of 1,000 ha of agroforestry over the period 2023 to 2030 resulted in a modest cumulative net removal of -24 GgCO_2, with This increases to -652 GgCO_2 for the period 2021-2050 due to an assumed increase in the agroforestry area of 8,500 ha by 2050 (Appendix Table A3).

Avoiding deforestation

Avoiding deforestation of 495 ha per year could reduce emissions in the AFOLU sector by 1,109 GgCO_2 over the period 2023-2030 and 4,222 GgCO_2 over the period 2023-2050. However, it is important to be mindful of the Nature Restoration Law, which was introduced on 22 June by the European Commission as a key element of the EU Biodiversity Strategy. As set out this proposal will require European Union member states to restore wetlands. In this context, avoiding deforestation will be challenging. Recent research shows that rewetting of temperate forest peat soils is not considered as a positive climate change mitigation action in the short term (Ojanen & Minkkinen, 2020; Black et al., 2022). Therefore, wetland restoration of forest land is not considered in this analysis.

Comparison of the Mitigation Scenarios

Table 7.8 below summarises the outcome of the modelling work by presenting the impact of the various scenarios on the GHG balance emissions profile. Detailed GHG profiles for each scenario are presented in appendix A.

Table 7. 8: *Summary of additional removals or a reduction in emissions from the forest modelling scenarios. The afforestation scenario represents future afforestation only. For MFL, all scenario are presented as the net decline in emissions relative to the BAU scenario*

	kt CO_2 eq.		
Measure	**2021-2030**	**2031-2050**	**Total (2021-2050)**
Afforestation	761	25,044	25,806
Extended rotation	4,479	**-4,252***	227
Broadleaf conversions on raised bogs	197	5,155	5,351
Additional agroforestry	24	627	652
Avoiding deforestation	1,109	3,113	4,222
Total	6.570	29,687	36,258

* negative values indicate an increase in emissions relative to the BAU scenario.

MACCs for different scenarios

Short term (2023-2030)

Alternative forest management by extension of rotation age has the highest short term abatement potential and this can be delivered at a profit to the land owner. The estimated abatement cost is €-88 per tCO_2 (Figure 7.8). Avoiding deforestation has a higher abatement potential, delivered at a low cost (€13.01 $t^{-1}CO_2$), when compared to afforestation (€236.80 $t^{-1}CO_2$). Agroforestry has a lower abatement cost (€176 $t^{-1}CO_2$) than afforestation due to the lower premiums and number of premiums (10 compared to 15/20 for forestry). In addition, the abatement potential of agroforestry is limited because only between 1,000 ha and 2000 ha is assumed to be established by 2030. Woodland conversion to birch on raised bogs has the highest short-term abatement cost (€305 $t^{-1}CO_2$) with a relatively low abatement potential 196 $GgCO_2$.

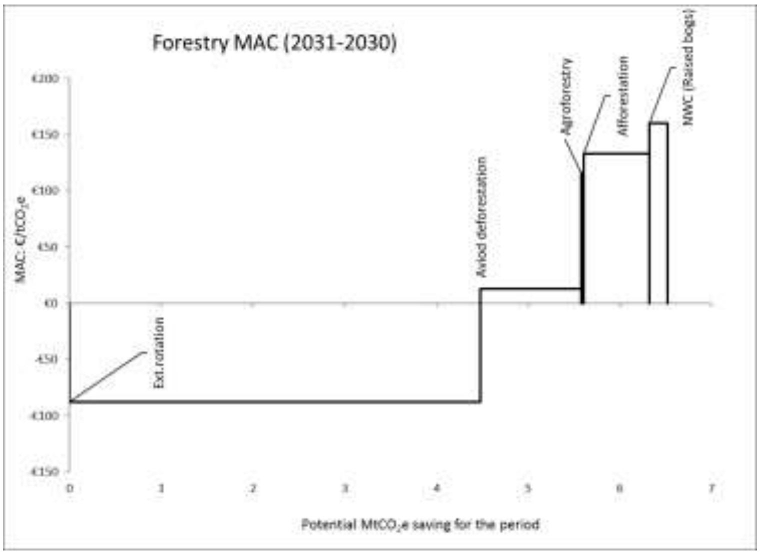

Figure 7.8: A marginal abatement cost curve (MACC) for afforestation and forest management measures showing the total abatement potential over the period 2023-2030.

Temporal trade-offs

The impact of afforestation and forest management measures dynamically change over time. Therefore, one needs to consider abatement costs and potential trade-offs over the short (2023-2030) and long term (2023-2050, Figure 7.8). For example, afforestation and woodland conversion has a low abatement potential and high cost in the short term. However, long term abatement costs and potentials are more favourable (Figure 7.9). The total abatement potential of afforestation and woodland conversion exceeds 30,000 kt CO_2 over the period 2021-2050, compared to less than 1,000 Gg CO_2 by 2030 (Appendix Tables A1 and A3).

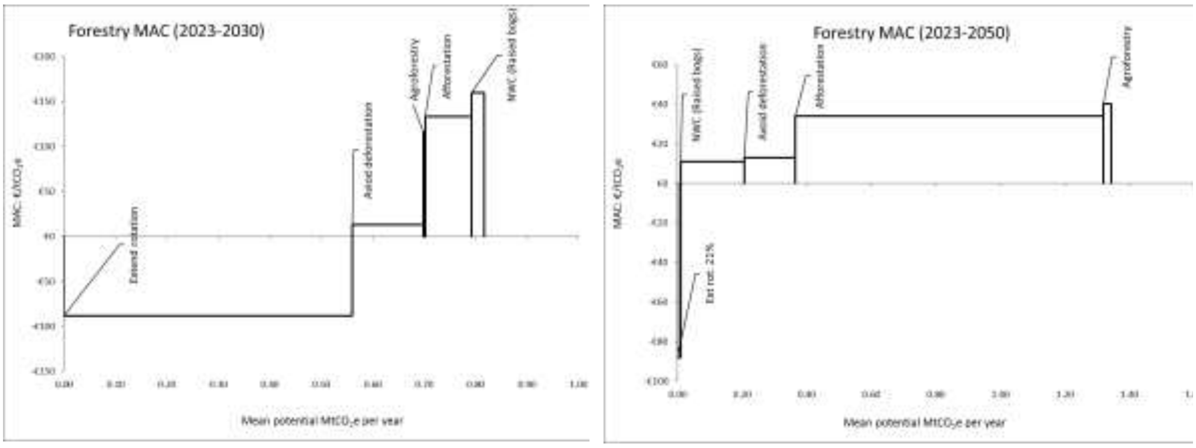

Figure 7.9: A marginal abatement cost curve (MACC) for afforestation and forest management measures showing the mean annual abatement potential over the periods 2023-2030 and 2023-2050.

The two forest management measures (extended rotations and woodland conversion) represent a good mix of short term and long-term measures (Figure 7.9) and the abatement cost of woodland conversion is much lower in the long term, €10.92 compared to €166 t^{-1} CO_2. Afforestation is clearly a good long-term strategy, showing a high annual abatement potential at a cost of €34 $t^{-1}CO_2$ (Figure 7.9).

Conclusions

Abatement options

This analysis shows that afforestation cannot deliver any significant short-term mitigation pathway before 2030. Afforestation is also one of the higher abatement cost measures in the short term. In contrast, forest management can technically offer some short-term mitigation but there are significant barriers that must be overcome to implement forest management mitigation measures, such as the economic impacts of extension of rotation. Extension of rotation age may offer the largest impact at the lowest abatement cost (Figure 7.8). The short-term contribution would also have a larger impact on minimising global warming to below 2 deg C. This finding is consistent with the impact assessment on implementation of the EU

LULUCF regulation (EC, 2021), which shows that the short-term abatement cost and potential for afforestation is much lower that it is for forest management.

A key feature of the BAU GHG profile of MFL is ongoing emissions from peatland forests and a transition from a net removal to a net emission of CO_2 by peatland forests after one to three rotations. Biodiversity measures such a peatland rewetting of forest lands actually result in negative climate change mitigation action in the short term due to high deforestation emissions (Ojanen & Minkkinen, 2020; Black et al., 2022). Woodland conversion in raised bogs would have significant long term GHG profile impacts, exceeding a 5,000 Gg CO2eq reduction for the period 2031-2050 without negatively impact future timber supply.

Climate action plan targets

If climate change action plan targets for the LULUCF sector are to be based a net-net accounting approach using the reference period 2016-2018, the reference value for the forest estate is a net removal -2,745 GgCO_2 per year (EPA, 2022). The challenge for the forest sector to contribute to future mitigation action by 2030 is that the BAU scenario (Figure 2) shows that there will be a deficit of 2,043 Gg CO_2 per year before any targets are set. In other words, the forest sector needs to introduce measures to ensure additional removals or a reduction in emissions totalling 20MtCO_2 over the period 2023 to 2023 just to stay at the 2016-2018 levels.

The identified forestry measures can potentially contribute a 6,570 GgCO_2 abatement potential for the period 2023-2030 (Table 4). However, this means that the forest sector will still require an additional reduction in emissions or increase in removals of 13,430 GgCO_2 from 2023 to 2030 to reach the same level as the proposed 2016-2018 target. Although the same accounting principles are adopted in the EU LULUCF regulation, there are flexibility mechanisms which compensate for a target shortfall due to the legacy effect of afforestation on organic soils and natural disturbances (EC, 2021). Forest management targets, were in the past, based on a net-net approach with a forward-looking baselines, to compensate for age class legacy impacts and indirect human induced impacts (Black et al., 2012). The other problem with a gross net target, using a base year, is that the impact of climate change on the emission profile form the LULUCF sector may cause additional emissions, which are not controlled through land use management. For example, emissions form drained soils may increase due to lower water tables and higher temperatures.

Implementation barriers

The afforestation rates assumed under the climate change action plan are still quite ambitious given the dramatic decline in afforestation in recent years. Although the available land for afforestation is potentially sufficient to meet assumed rates, future afforestation on any organic soils should be avoided because of long term emissions. More than half of sites afforested in the past are located on organic soils. Afforestation on mineral soils only presents a further challenge because:

- Land price and land expectation value of mineral sites are higher than the current value of land being converted to forestry. However, the new forestry programme due in 2023 may partially address this barrier;
- The licencing and EU habitats directive limitations means that less land is potentially available than it was the past;
- Forest nurseries need a ramping up period of 2 to 3 years to increase seedling production to meet increase demand if private afforestation increased. Therefore, it is not possible to double afforestation rates in one year. The climate change plan targets should consider a more gradual increase in line with nursery production capacity;
- Other agricultural schemes, or nitrate directive rules may further limit land available for forestry.

Economic incentives for implementation of mitigation measures in Irish forests afforestation and forest management) would be possible through a voluntary trading mechanism. Although EU strategy is being developed to introduce such mechanism (i.e. C farming), Ireland has not developed these national trading mechanisms to the same extent that other EU countries have. Therefore, development of a national trading mechanism may come too late to capture 2023-2030 mitigation action under forest management pathways. Participation in existing international schemes, such as the Voluntary trading scheme (VCS) is limited due to economy of scale. Therefore, privately owned forest areas are too small to cover project set up, monitoring and verification costs to register a project under the VCS.

The Climate Action Plan 2021 includes a commitment for the Government to develop an enabling framework to facilitate the development of a carbon farming initiative in Ireland. At EU level, the European Commission adopted a Communication on Sustainable Carbon Cycles in December 2021, setting out how to increase removals of carbon from the atmosphere. The Communication details actions to support carbon farming and upscale this green business model to better reward land managers for carbon sequestration and biodiversity protection. The Commission is working on a regulatory framework for the certification of carbon removals, with the intention of publishing a proposal by the end of 2022 and expected entry into force by the end of 2023. In the interim, an expert group is being established from forestry, agriculture & environmental specialists to advise on plans for the new framework, where Member State authorities and stakeholders can exchange best practices on carbon farming and share experiences. The work of the expert group will lead to the development of carbon certification methodologies setting-out how land-owners will be rewarded for removing carbon through their management activities.

It should be stressed that most of the predicted increase in harvest under the BAU scenario will come from privately owned forest land. Therefore, creation of policy or financial incentive to implement measures to extend rotation age in private forests will be difficult for the following reasons:

- Landowners may not wish to delay their investment pay out from clear felling operations even though extended rotations will return a higher discounted profit.
- Private forests are represented in the portfolios of pension and investment funds. These investment returns are based on discounted cashflows and the timing of harvesting can be based on current silvicultural practice.
- The timber processing sector may not support a reduction is the potential level of future harvest albeit that short-term timber harvest (up to 2030) would be maintained at the current rate of 4Mm^3 per year. This sector has invested in processing facilities on the basis of the projected increase in timber supply;
- The risk associated with extending rotation through exposure to disturbance events such as windthrow will also act as a negative incentive to many landowners.

The implementation of CCF scenarios is limited because of a scientific knowledge gap with regards to how CCF GHG profiles may look. To date, preliminary CCF modelling approaches remain to be validated, so the impact of transformation to CCF is subject to large uncertainties. In addition, significant barriers exist with regard to implementation of the measure. Our analysis suggests that most of the suitable area (88 kha) for transformation CCF is within the private estate. This represents a significant shift in forest management practice requiring transformation of over 3,000 ha per year from conventional to CCF management. A survey conducted by Vitkova et al. (2013) showed that only 15,000 ha of forests in Ireland are under CCF management. Despite the current grant incentive for CCF management, additional incentives are required:

- Private owners may be reluctant to switch to CCF because of the larger loss in clearfell revenues. The current CCF grant hardly covers management costs and not the potential short-term cash flow losses;
- The milling industry does not pay a premium of large diameter logs harvested from economically viable CCF operations. Not all sawmills can process the larger diameter logs. Additional market streams need to be developed for this product;
- There is a lack of CCF expertise, particularly in relation to marking of stands and harvesting. Large training programmes are required to rectify the skills gap.
- A review of the CCF literature suggests that the impact of CCF versus conventional management is still unclear (Black et al., 2022). Models are being developed under the COFORD funded Continufor project, but these will only be available by 2023/4. No climate change mitigation impacts associated with CCF can be done before robust models are developed.

Agroforestry is a relatively underdeveloped practice in Ireland and the limit of the 5-year premium payment under the current, or future schemes, may not provide enough incentive.

Exchequer Costs

Based on the new forest creation programme, maximum cumulative costs to the exchequer would be €443M by 2030. However, if this rate of afforestation is achieved, the ultimate cost would rise to €851M by 2050. Assuming 1000 ha of agroforestry, the exchequer cost would be €10M by 2030 and €12m by 2050. Therefore, the total cost would be €863M.

Table 7. 9: *Exchequer costs associated with forestry measures*

Year	Cumulative Cost €M 1 - Forest Creation	Cumulative Cost €M 2 - Agroforestry	Cumulative Cost €M Total
2023	42	1	43
2030	433	10	443
2040	750	12	762
2050	851	12	863

24. Hedgerows

	Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
New Hedgerows	Pathway 1	3.55	70.92	21.21	7.95	159	1678 to 2242
	Pathway 2	7.09	142	42.42	15.9	318	1678 to 2242
Management	Pathway 1	15.82	158	49.5	-0.07	-0.72	-1.90 to -2.15
	Pathway 2	23.73	237	74.2	-0.11	-1.08	-3.22 to -4.55
All	Range	3.55 to 23.73	70.92 to 237	21.21 to 74.2	-0.11 to 15.9	-1.08 to 318	-4.55 to 2242

See A1.18 for full assumptions and results

Hedgerows can sequester Carbon in aboveground biomass, belowground biomass and in soil organic carbon pools. Management has a large impact on the ability of hedgerows sequestration capacity, with aboveground biomass sequestration in highly managed hedgerows severely curtailed. A recent EPA- funded project (Farm-Carbon) has sought to assess the impact of a) new planting and b) hedgerow management on total C sequestration. Using aerial photography and biomass measurements, hedges have been divided between regular and irregular hedges.

Emission and uptake assumptions

All data was obtained from Black et al. (2023). Hedges are divided between irregular and regular hedges. It was assumed that 20,000 km of new hedges (at a combined SOC/biomass sequestration rate of 3.55 $tCO_2\ km^{-1}$) would be installed and 50,000 km of regularly cut managed hedges be unmanaged for five years in order to increase width by a minimum of one metre with no limit on height. This would result in 282 $tCO_2\ yr^{-1}$.

Table 7. 10: Impact of new hedgerows and hedgerow management on biomass and soil carbon stocks

Scenario			Biomass	SOC	Total $ktCO_2e$
Moderate	20000km	New	2.706	0.84	70.92
	50000km	Managed to unmanaged	3.3464	0.88	211.40
Enhanced	40000km	New	2.706	0.84	141.84
	75000km	Managed to unmanaged	3.3464	0.88	317.10

Costs

Hedge costs are detailed in table 7.11. New hedgerows are a small net cost 2.24 per tCO_2e while hedge management is a cost saving due to the reduction in fuel consumption and time cost.

Table 7.11: *Costs associated with planting new hedgerows and cost savings associated with reduced management.*

New Hedge costs			
Cost	For every 100 m of new hedge - buy 550 hawthorn and 50 other species		
Plants per m	€4.85		
Silage wrap and plant protection	€1		
Labour & fuel	€3.4	€9.25 m^{-1}	

Hedge management	per hour cost	
Tractor (capital) cost	€10.00	
Labour cost (€18/hour gross)	€18.30	
Fuel cost (7L/hour based on a cost of €1.30 /L)	€9.10	
Repair cost (€3/hour X 40 hours) - €120/week;	€3.00	
Insurance cost (€1.50/hour X 40 hours) - €60/week;	€1.50	
Hedgcutter	€15.00	
Total	€56.90	
3 km per hour	€18.97	per km
	€758,666.67	
reduce from cutting 50,000km every year to every 5 years	-€3.59	saving p.a.

Sensitivity analysis

Emissions reduction: This measure is sensitive to the assumed proportion of regular or irregular hedges as the sequestration rate is three times higher for irregular hedges. This is mainly due to the larger mean width of these hedges.

Costs: The cost of saplings is the principal cost driver in 'new hedges' sub-measure, whilst fuel cost is that main variable for 'hedge management' Variation in the fuel cost of between €0.53 and €1.30 per litre was used for the low and high cost scenario respectively.

Barriers to uptake

Over the last decade, there has been a gradual decline in hedgerows in order to maximise the growing area. In addition, the definition of 'good hedgerow management' by DAFM has run counter to promoting the maximum CO_2 sequestration. Incentivisation under new agri-environmental schemes will be vital to a) encourage new planting but also encourage enhanced management. Research on using different, faster growing species within the hedge mix is also required.

Exchequer Costs

Current hedgerow grants are for €5.47 m^{-1} for a five year period. Under the moderate and enhanced mitigation pathway, 20,000 km and 40,000 km is projected to be planted. This would result in a cost of €109.4M and €218.8M at the grant-aided rate of €5.47 per metre. Each landowner is limited to 750m of grant-aided hedge laying and as historically circa 50,000 farms is the number that has applied for agri-environmental schemes, it is unlikely that planting would be higher than 40,000km with associated maximum costs of €218.8M.

25. Enhanced grassland management

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Pathway 1	146	358	171	-11.6 to -38.0	-27.7 to -85.0	-77.47 to -237
Pathway 2	230	556	269	-7.51 to -33.3	-21.47 to -92.4	-38.36 to -162
Range	146 to 230	358 to 556	171 to 269	-7.51 to -38.0	-21.47 to -92.4	-38.68 to -237

See A1.19 for full assumptions and results

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 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 though reduced tillage events or to direct drill in place of inversion ploughing.

2. Increasing the abundance of legume species in the 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 tC 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 by mainly by soil and climatic factors (Torres-Sallan et al. 2017). If 752,000 ha are optimally managed, this will result in 358 kt CO_2-e yr^{-1}. Costs include extra lime, clover seed, fuel usage and farmer time, offset with higher grass yields. Thus, the measure interacts with 'improved NUE' and 'clover' and the overall cost savings has been allocated between N_2O reduction and C sequestration based on the proportion of GHG mitigation achieved.

Assumptions

- **Pathway 1** 752kha ha limed by 2030 with linear uptake distribution. Clover reseeding rate of 6% on dairy and 1% on non-dairy farms with an uptake rate of 35% on dairy and 25% on non-dairy farms. This resulted in 472,080 ha sown with clover.
- **Pathway 2:** 1090 kha ha limed by 2030 with linear uptake distribution. Multi-species reseeding rate of 10% on dairy and 3% on non-dairy farms with an uptake rate of 70% on dairy and 50% on non-dairy farms. This resulted in 757,400 ha sown with clover.

Soil Sampling Costs: A soil sample should be taken for every 3 hectares of land targeted under this pathway at a cost of €25 per sample to be tested in the laboratory (Teagasc, 2020b).

Liming Costs:

- Low cost scenario – Fuel (for spreading) = €0.53/l, N/P fertiliser replacement value N = €1.20, P =€2.62, Lime = €25 per tonne including labour cost
- High cost – Fuel (for spreading) = €1.30/l, N/P fertiliser replacement value N = €2.60, P =€3.84, Lime = €35 per tonne including labour cost

Clover

- *Low cost scenario* – Clover seed was priced at €12 ha^{-1} with a seed rate of 5kg ha^{-1}. Contractor rates of €118 per hectare are assumed for reseeding of grassland with clover (FCI, 2020). Fuel (2.5l per hectare for spreading if seed is broadcast) was €0.53 l^{-1}. Under the low cost scenario, the mean N fertiliser replacement value was set at €1.20 kg^{-1} N. After five years, re-seeding was assumed to be required, with seed oversown b the farmer. As a result, no labour cost was assumed.
- *High cost scenario* – Multispecies seed was priced at €66 per 12 kg bag with a seed rate of 30 kg ha^{-1}. Fuel (2.5l per hectare) was priced at €1.30 l^{-1} with an assumed N

fertiliser replacement value N of €2.70 kg^{-1} N. Partial re-seeding by over-sowing was assumed to occur after five years at half the seed rate. No labour cost was assumed.

Sensitivity analysis

Emissions: Liming and clover were modelled using DailyDAYCENT and the mean rate of sequestration was modelled at 0.5 tCO_2e ha^{-1} yr^{-1}. This value will vary considerably depending on soil type. The range of sequestration was -0.1 to 0.84 tCO_2e ha^{-1} yr^{-1} for clover/multi-species and -0.15 to 0.67 tCO_2e ha^{-1} yr^{-1} for liming.

Costs: Primary cost sensitivities are (in order) a) price of mineral fertiliser, b) cost of lime, c) the cost of soil sampling, d) the cost of fuel and e) the cost of labour

Inventory Reporting and Requirements

In order for this measure to be implemented, a revision of the land-use and land-use management factors will be required. It is likely that a model will need to be incorporated in order to account for these measures and the timeline for his to occur is likely to be at least five years.

Barriers to Uptake

Both liming and the use of legumes/ multi-species swards complement each other. In order to establish clover in the sward, soil pH and soil P/K levels need to be correct. The establishment of both multi-species swards and clover also requires a high level of sward management, which is a cost in terms of farmer time, which can be especially problematic for many livestock farmers, who hold other jobs and farm part-time. The use of the con-acre model of short-term land leasing is a significant impediment to promoting good soil husbandry.

Exchequer costs

These costs are detailed in the liming and clover/MSS measures.

26. Water Table Management (Peat soils)

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	121	646	89	5.46 to 6.05	36.4 to 40.3	45.10 to 49.97
Pathway 2	162	1616	665	7.29 to 8.07	72.9 to 80.7	45.10 to 49.97
Range	121 to 162	808 to 1616	444 to 665	5.46 to 8.07	36.4 to 80.7	45.10 to 49.97

See A1.20 for full assumptions and results

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 Department of Agriculture Food and the Marine (DAFM) if they exceed 15 hectares, regulations pertain only to new drainage work and not to the maintenance of existing drainage systems. The 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 (c.f. Burdon, 1986) when the regulations mentioned above did not exist. For National Inventory Reporting purposes it is therefore assumed that most farmland on poorly draining carbon rich soils has been artificially drained at some stage in the past. However, it should be noted that ongoing work aims to refine this assumption.

Emissions Assumptions

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. Total emissions are derived from a number of sources including 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 nitrous oxide (N_2O) emissions from soils and methane emissions associated with re-wetting (Table 4.12).*

Table 7. 12: *Difference of emissions from drained and rewetted organic soils (t CO2e ha-1yr-1)*

	Emissions Drained	*Emissions Rewetted*	*Δ Emissions*
Land use	*[t 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*

Uptake assumptions

This analysis was performed under the assumption that there is circa. 339kha of agricultural land on drained organic soils. This figure is, however, highly uncertain. An ongoing analysis is indicating that the amount of effective in-field drainage is likely lower than currently assumed and the maintenance status of these drains is highly uncertain (Tuohy et al, in review).

Pathway 1 assumed that the water table of 40kha of drained agricultural peat was raised to between 10-30cm below the soil surface, while Pathway 2 assumed 80kha of water table manipulation.

If artificial drainage was stopped completely and natural water table conditions were restored, 40,000 hectares of re-wetted grassland would result in cumulative emissions savings of 808 kt CO_2e and 1616 kt CO_2e in total by 2030.

Cost assumptions

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 between €50 and €190 ha^{-1}. The main cost associated with blocking drains and maintaining drain blockage and re-profiling of peat banks, if required (Table 4.13). Costs will be specific to each site and the future management goals. If restoration occurs there is an added cost associated with the installing and maintenance of sphagnum plugs. Both the low cost and high cost scenario's assumed that 10% of peatland management included restoration.

Table 7. 13: Cost assumptions for peat management

	Low €/ha	High €/ha	Mean €/ha	Okumah et al. 2019, Artz et al. 2018
Dam drains with peat	**119.77**	**519.77**	**331.40**	
Dam drains (plastic)	**86.05**	**1030.23**	**462.79**	
Reprofiling peat banks	**0.00**	**1105.81**	**1329.07**	
Introducing Sphagnum spp.	**550.00**	**1410.47**	**982.56**	
Income forgone	**50.00**	**190.00**	**120.00**	
Total (no restoration)	**169.77**	**2326.05**	**1247.91**	
Total (with restoration)	**719.77**	**3736.51**	**2228.14**	

Sensitivity analysis

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, 0.5 Mt CO_2-e would be abated compared to 0.808 Mt CO_2-e if the 40,000 ha were converted from 2023. In addition, a large portion of previously drained grassland on organic soils may already be re-wetted as drains have fallen into disrepair. This would result in reduced reported CO_2 loss from a much larger area at little cost (i.e. the cost of mapping these areas and verifying emissions reductions).

The costs were principally dependent on a) how drains were blocked, b) whether re-profiling was required and c) whether restoration to sphagnum bog occurred. Okumah et al. (2019) estimated that damming costs could vary between £105 and £5883 per hectare depending on whether peat, plastic or rock was used. Rock damming was considered prohibitive and only the cost for plastic or peat damming was considered, with costs varying between €119 and €1030 per hectare.

Barriers to uptake

There are several barriers to uptake of this measure. There are several knowledge barriers in terms of the extent of emissions on drained agricultural peats. A study on UK and Irish sites indicated that for every 10 centimetres increase in water table, a reduction of 3 tonnes of CO_2 per hectare per year would occur (Evans et al., 2021). Currently the National Agricultural Soil Carbon Observatory (NASCO) is monitoring eight sites which will establish robust emission factors. In addition, there are some technical obstacles in terms of re-wetting one site without affecting neighbouring land. This is particularly pertinent where, for example, the landowner wants to rewet only a portion of their farm, or where a landowner wants to rewet, but neighbouring landowners do not. As observed above, costs are also potentially high and these costs do not account for any changes in the price of land (which will almost certainly occur) upon water-table manipulation.

7.2.3. Enhanced cropland management

27. Cover crops

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Moderate	33.1	62.6	36.4	2.00	3.78	60.5
Enhanced	41.2	87.4	46.5	2.49	5.29	179
Range	72.1 to 90.1	151 to 189	33.7 to 80.9	2.00 to 3.76	3.78 to 7.98	60.5 to 270

See A1.21 for full assumptions and results

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).

Emissions Assumptions

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 was estimated to be 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 $CO_2e\ ha^{-1}\ yr^{-1}$, 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 $CO_2e\ yr^{-1}$.

Uptake assumptions

- Pathway 1: One-third of spring crop area (50 kha) had cover crops applied.
- Pathway 2: 75kha of spring crops had cover crops applied.

Cost assumptions

Low cost scenario: Costs involved include seed at €37 per ha^{-1}, fuel and ground preparation (27.8 litres ha^{-1} at €0.53 per litre) a cost saving of 30 kg N $ha^{-1}\ yr^{-1}$ at €1.20 per kg N saved (Kindler et al. 2011). Mean total costs ranged from €1.51 million to €1.93 million for the

Pathway 1 and Pathway 2 respectively, with fertiliser cost savings of €1.04 million (Pathway 1) and €1.34 million (Pathway 2). This resulted in a net cost of between €0.459 and €0.586 million yr^{-1}. By 2030, net total costs were estimated to be between €789k and €1.1 million for Pathways 1 and 2 respectively with marginal abatement costs of €13.50 per tonne CO_2e for both Pathways

High cost scenario: Costs involved include seed at € 47 per ha^{-1}, fuel and ground preparation (€25.09 ha^{-1}) a cost saving of 30 kg N ha^{-1} yr^{-1} at €2.70 per kg N saved (Kindler et al. 2011). Mean total costs ranged from €2.42 million to €2.72 million for pathway 1 and pathway 2 respectively, with fertiliser cost savings of €2.27 million (pathway 1) and €2.90 million yr^{-1} (pathway 2). This resulted in a negative net cost of between €141,000 and €191,000 yr^{-1} for Pathways 1 and 2 respectively.
By 2030, net total costs were estimated to be between €258k and €360k for Pathways 1 and 2 respectively with marginal abatement costs of €4.41 per tonne CO_2e for both Pathways

Sensitivity analysis
Emissions: The principal sources of uncertainty were uptake rate and the *per hectare* rate of sequestration/GHG reduction, with total area under cover crops ranging from 50.35 kha for Pathway 1 to 127.3 kha for Pathway 2. As a result the emissions reduction varied from 62.9 to 151 $ktCO_2e$ yr^{-1}. This study assumed a net sequestration rate of 0.73 tCO_2e yr^{-1} and N_2O reduction of 0.49 tCO_2e yr^{-1}. Values for the net sequestration rate may vary from 0.48 to 1.26 tCO_2e yr^{-1} (Pellerin et al. 2013) while the N_2O savings can range from 0.1 to 0.5 tCO_2e yr^{-1} (Pellerin et al. 2013, Schulte et al. 2012, Lanigan et al. 2018). This would result in a three-fold variation in the GHG reduction rate associated with cover cropping.
Costs: The principal sources of cost variation were the price of seed, fuel usage and the amount/cost of N saved by the measure. Net costs varied from €19.24 to €57.29 per tonne CO_2e abated.

Inventory Inclusion
The incorporation of SOC sequestration will require the development of a Tier 2 Land management factor in order for additional sequestration to be included in national inventories. Similarly, the reduction in N2O emissions associated with the reduction in leached N will require either a) an altered N leaching factor associated with cover crops or b) reduced N fertiliser application associated with cover crops.

Barriers to uptake
Cost is the main barrier to uptake along with a large degree of uncertainty as to the amount of N saved by this measure.

Exchequer Costs

While Cover Crops are covered within general agri-environmental schemes, there has been no explicit payment.

28. Straw Incorporation

Pathway	Abatement in 2025 (ktCO2e yr-1)	Abatement in 2030 (ktCO2e yr-1)	Mean abatement (ktCO2e yr-1)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	29.7	67.2	34.5	4.21 to 4.72	9.53 to 10.70	142 to 159
Pathway 2	39.2	95.2	46.5	5.56 to 6.24	13.5 to 15.16	142 to 159
Range	29.7 to 39.2	67.2 to 95.2	34.5 to 46.5	4.21 to 6.24	9.53 to 15.16	142 to 159

See A1.22 for full assumptions and results

Straw incorporation increases SOC, as organic matter is directly inputted back into the soil. For every 4t straw incorporated over 15-20 years, a 7-17% increase in SOC (top 15cm only) has been observed (depending on whether reduced tillage was also applied, (see Powlson et al. 2008, van Groenigen et a. 2011). This results in a net annual sequestration of 1.08 tCO_2 ha^{-1} yr^{-1}.

Emissions Assumptions

It was assumed that the incorporation of straw increased SOC by 1.08 tCO_2 ha^{-1} yr^{-1} over a 30 year period (van Groenigen et al. 2011). In addition, straw was assumed to displace 14.4 kgN ha^{-1} yr^{-1}.

Uptake assumptions

- Pathway 1: One-quarter of the cereal area (60 kha) had straw incorporated
- Pathway 2: 85 kha of cereals had straw incorporated – principally oaten, barley and some rape straw.

Cost assumptions

Low cost scenario: It was assumed in both scenarios that 23 bales (4x4 @150 kg) per hectare were produced. In terms of costs, the price forgone for straw bales was €16 per bale with the cost of chopping straw estimated at €15 per hectare. Cost savings included the cost of baling, handling and turning, which was costed at €6.50 per bale, with transport at €2 per bale. N savings (€1.20 per kg) was €0.63 per bale while P & K was €1.50 per bale.

High cost scenario: Assuming 23 bales per hectare were produced, the price forgone for straw bales was €21 per bale with the cost of chopping straw estimated at €16 per hectare. Cost savings included the cost of baling, handling and turning, which was costed at €7.50 per bale, with transport at €3 per bale. N savings (€2.70 per kg) was €1.70 per bale while P & K was €2.74 per bale.

Table 7. 14: Costs per hectare associated with straw incorporation

		Low cost per ha	High cost per ha
Price forgone	Price per bale	€414.00	€483.00
Chopping cost		€14.00	€16.00
Saving	Baling	€92.00	€115.00
	Handling & Turning	€57.50	€58.50
	Transport	€46.00	€69.00
	P & K per bale	€34.50	€63.02
	N @ 1.20 per kgN	€17.39	€39.10
	Total	€230.00	€305.52

Sensitivity analysis

Emissions: The principal sources of uncertainty were uptake rate with the total area varying from 65 kha to 128.9 kha between the pathway 1 and pathway 2 pathway.

Costs: The principal sources of cost variation were the price of straw and the NPK saved by the measure. Net costs varied from €120 to €139 per tonne CO_2e abated.

Inventory Inclusion

The inclusion of straw incorporation will require the development of a Tier 2 Land management factor in order for additional sequestration to be included in national inventories. Similarly, the reduction in N_2O emissions associated with the reduction in N_2O would require reduced N fertiliser application associated with straw incorporation.

Barriers to uptake

Cost is the main barrier to uptake along with a large degree of uncertainty as to the amount of N saved by this measure and the potential output price for straw in any year.

Exchequer Costs

Exchequer costs were based on the Straw Incorporation Scheme whereby Wheat, Barley and Oaten Straw is valued at €250 per ha and OSR straw at €150 per ha, with eligible areas of between 5 and a maximum area of 40 ha per farm. Total costs are €16.06M for Pathway 1 and €25.8M for Pathway 2.

Table 7. 15: *Exchequer costs associated with crop measures*

		Area		**Exchequer Cost**	
	Total area	**Pathway 1**	**Pathway 2**	**Pathway 1**	**Pathway 2**
Wheat	60,000	16,000	30,000	€4,000,000	€7,500,000
Barley	174,000	23,000	70,000	€5,750,000	€17,500,000
OSR	11,000	2,000	5,800	€300,000	€870,000
Oats	28,400	24,000	24,000	€6,000,000	€6,000,000
Total area	234,000	65,000	129,800	€16,050,000	€25,870,000

29. Enhanced Manure Application on Arable Soils

Pathway	Abatement in 2025 (ktCO2e yr-1)	Abatement in 2030 (ktCO2e yr-1)	Mean abatement (ktCO2e yr-1)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO2e
Pathway 1	6.00	31.95	10.90	-0.100 (low cost) -0.294 (high cost)	-0.413 (low cost) -1.60 (high cost)	-12.94 (low cost) -50.05 (high cost)
Pathway 2	8.00	55.91	46.5	0.075 (low cost) 0.392 (high cost)	-0.723 (low cost) -2.80 (high cost)	-12.94 (low cost) -50.05 (high cost)

See A1.23 for full assumptions and results

This measure focuses the application of bovine and porcine manures to arable soils, which are typically have substantially lower soil organic carbon levels, compared to grassland soils in Ireland (Kiely et al. 2013). In addition, the application of manures to cropland have been estimated to sequester additional C compared to manure application to permanent grassland, where stocks may be at or near saturation (Moxley et al. 2014, Bol et al. 2010).

Emissions Assumptions

Using DAYCENT, the impact of manure application to cropland and grassland was modelled with application of 30 m^3 per hectare. Model runs were performed until SOC stocks were at equilibrium. The SOC difference between the beginning and end SOC stocks for grassland and cropland were used to calculate the addition impact of SOC on cropland soils. The additional sequestration rate was 0.32 tC ha^{-1} yr^{-1} for cropland and 0.20 tC ha-1 yr-1 for grassland, which compared well to previously measured and modelled values (Moxley et al. 2014, Einarsson et al. 2021). Therefore, the additional sequestration was 0.12 tC ha^{-1} yr^{-1}.

Uptake Assumptions

Pathway 1 assumed that 8% of available manures were applied onto 63.9 kha of cropland.

Pathway 2 assumed that 14% of available manures were applied onto 112 kha of cropland.

Cost assumptions

Low cost scenario: Transport was calculated at €3.16 per m^3 slurry, assuming a mean 30km radius for manure transport, with spreading of manures costed at €2.40 per m^3 slurry assuming €0.53 per l for green diesel. The N, P and K savings assumed that slurry contained

1.18 kg TAN, 0.7 kg P and 3.5 kg K per m3, with N, P and K prices of €1.20, €2.62 and €0.78 per kg respectively.

High cost scenario: Transport was calculated at €4.66 per m^3 slurry, assuming a mean 20km radius for manure transport, with spreading of manures costed at €5.3 per m^3 slurry assuming €1.30 per l for green diesel. The N, P and K savings assumed that slurry contained 1.18 kg TAN, 0.7 kg P and 3.5 kg K per m3, with N, P and K prices of €2.60, €3.87 and €1.56 per kg respectively.

Exchequer Costs

There is no exchequer cost associated with this measure.

7.3. Energy measures

30. Biomethane

Pathway	Abatement in 2025 (ktCO₂e yr⁻¹)	Abatement in 2030 (ktCO₂e yr⁻¹)	Mean abatement (ktCO₂e yr⁻¹)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO₂e
Biomethane Pathway 1	85.25	266	132	-16.9	-52.8	-198.5
Pathway 2	79.92	1374	510	-39.6	-753	-496
Range	26.4 to 85.25	220 to 1518	126 to 378	-16.9 to -39.6	-12.4 to -753	-34.4 to -496

See Tables A1.23 & A1.24 for details

Anaerobic digestion of biomass produced from Irish grassland (ie. grass fed-biomass) would produce biogas (55% methane) that could be used directly for heat and electricity generation, or the biogas 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, SEAI 2017). 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 and slurry-fed biomethane production overcomes the high CO_2 emissions associated with the land-use change associated with the conversion of permanent grassland to crops such as maize.

Emissions Assumptions

Biomethane

Pathway 1 has 50 plants producing 1.0 TWh of gas, while **Pathway 2** has 285 plants producing 5.7 TWh. Each plant produces between 20 GWh and displaces 74t CO_2e per TJ produced. Feedstock is 20.8kt fresh weight silage and 14000 tonnes slurry.

Cost Assumptions

Cost assumptions for biogas and biomethane are detailed in Table A1.23. For biomethane, two cost scenarios were examined, a low and high cost scenario. The CAPEX cost is similar under both scenarios (circa €6.8M), but the interest and OPEX costs are higher under the high cost scenario (€4.09M and €2.7M for the high and low cost scenarios). In particular, the cost of feedstock (grass silage) increased from €33 per bale to €52 per bale. However, under the high cost scenario, the feedstock cost increase is outstripped by the increase in heat and gas price (from 5 and 7 cent respectively to 10 and 14 cent per kWh). The target for biomethane would require between 205 and 285 plants.

Sensitivity analysis

In terms of emissions, the uncertainty associated with fossil fuel displacement is relatively low. The most sensitive variable would be the size and number of plants, which would impact mainly on CAPEX cost rather than fossil fuel displacement. The principal uncertainities are in terms of costs with the principal sources of uncertainty being a) price of energy, b) price of feedstock and c) CAPEX costs. Under the high cost scenario, biomethane is cost negative over the lifetime of the plant. However, a 10% reduction in the energy price under the high cost scenario would be enough to make the measure cost positive.

Inventory incorporation

This measure can be readily incorporated into national inventories as the fossil fuel displacement with biomethane or renewably-sourced heat and power all have constant fixed emission factors. The activity data that would need to be collected are a) the power/gas output per plant. In addition, the cultivation of the feedstock must comply with Renewable Energy Directive (RED II) in that a 65% and 80% total savings in fossil fuel GHGs across the full life-cycle of biomethane production is required in transport and heat respectively. As a result, a thorough life-cycle analysis of the silage and manure management system is also required.

Barriers to uptake

The main barrier for uptake is fiscal in that a large investment in infrastructure (both in terms of plants and also connectivity to the gas grid). The cost of feedstock may also be an impediment if grass cultivation costs remain high. However, this can be reduced considerably if the digestate produced by the plant displaces other NPK sources.

Exchequer costs

Costs were based on a REFIT 3 balancing payment of €9.90 per MWh. Total exchequer costs would equate to €55.31M per annum or €442M to 2030. The renewable Gas Forum of Ireland calculate that capital investment costs for the government target would be €1.5 billion.

31. Wood Energy

Pathway	Abatement in 2025 (ktCO$_2$e yr^{-1})	Abatement in 2030 (ktCO$_2$e yr^{-1})	Mean abatement (ktCO$_2$e yr^{-1})	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO$_2$e
Pathway 1 & 2	1434	1518	1292	-49.7	-63.1	-38.66
Range	621 to 1434	708 to 1518	512 to 759	-28.5 to -49.7	-31.6 to -56.6	-20.55 to -45.5

See Table A1.25 for details

Forestry thinnings and waste residue can be utilised in heat production or in combined heat and power (CHP) systems.

Emissions and Uptake Assumptions

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 Murphy et al (2014), the resource availability comprises 81 - 267 ktoe (kilotonnes of oil equilvalent) from thinnings between 2021-2030, 142 -181 ktoe for sawmill residues and 26.2- 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 MtCO_2-e from 2012-2030 and a maximum abatement of 0.85 MtCO_2-e by 2030.

Cost Assumptions

Costs were based on €2.5 GJ^{-1} for residues and €6 GJ^{-1} for forestry woodchips (SEAI 2017b). *Low cost scenario*: 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 €15 per tonne). The main cost was transport and labour (priced at €19 per m^3). Mean total costs were -€5.2 million from 2021-2030, with 2025 and 2030 costs of -€6.37 million and -€6.31 million.

Sensitivity Analysis

In terms of fossil fuel displacement, the main uncertainty is the supply of wood residues as the energy density and fossil fuel displacement factors are constant. This measure strongly interacts with Forestry management, as any delay in clearfelling may reduce the wood residue available, thought this may not necessarily occur if thinnings occur in place of a clearfell event. The cost variation was sensitive to energy price, both in terms of income for residues and also fuel costs for transport costs.

Inventory inclusion

Emission factors are already in the inventory. Activity data required would be sales of firewood and/or firelogs.

Barriers to uptake

The main barrier is forest management as delays in clearfelling or thinning would impact supply. Afforestation rate will not impact on this measure to 2030 although ongoing supply would be impacted in the absence of increased afforestation rates.

Exchequer Costs

These costs are covered in the Forestry measures

32. Biomass - Short Rotation Coppice & Miscanthus Biomass for Electricity and Heat Production

Pathway	Abatement in 2025 ($ktCO_2e\ yr^{-1}$)	Abatement in 2030 ($ktCO_2e\ yr^{-1}$)	Mean abatement ($ktCO_2e\ yr^{-1}$)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO_2e
Heat	95.75	171	105	-1.91	-3.45	-20
CHP	89.25	168	98.2	-0.89	-1.61	-10
Range	50.25 to 95.75	146.3 to 178.7	56.4 to 105	-0.51 to -1.91	-1.46 to -3.45	-10 to -20

See Table A1.26 for details

The Climate Action Plan sets out an overall target of reducing CO_2e emissions from the energy sector by 4 $MtCO_2e$ by 2030, with biomass being a principle renewable technology for meeting large scale heat demand. While the primary source of biomass for heat generation is expected to come from forestry resources (Measure 22), biomass from energy crops is also expected to make a small 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 10,000 ha of willow and Miscanthus is planted on grassland.

All major inputs and sinks of the major greenhouse gases (GHGs), 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 herbicide application and by fertilization. The last harvest is succeeded by two herbicide applications to kill the crop and ploughing to remove the crop.

Emission Assumptions

For this analysis, 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 tonnes of dry matter per hectare were assumed. Gross GHG abatement from the substitution of fuels for heat (kerosene) was based on fossil fuel replacement and the emission factors used in the National Inventory Report (Duffy *et al.* 2022). Net GHG abatement was calculated by subtracting the GHG footprint of willow production from gross GHG abatement.

Cost assumptions

The cost of this measure was calculated using returns for willow production produced by Thorne (2011) and updated with current fuel and input costs. 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 PM10) and oxides of nitrogen and sulphur (NOx and SOx) can be emitted during combustion, particularly compared to oil or gas.

Sensitivity Analysis

The main source of uncertainty is the area of these crop that are planted. Over the last decade, the total are under SRC and Miscanthus has shrunk by 1000 ha rather than expanded. The main cost variable is a) energy price and b) fertiliser and input prices, although it is envisaged that animal manures would be utilised as a fertiliser source for this measure in order to comply with the Renewable Energy Directive.

Inventory Incorporation

In terms of fossil fuel replacement, this measure would show up as a reduction in fossil fuel consumption for heat generation.

Barriers to Uptake

There are considerable barriers to the uptake of this measure. This is principally as a result of the mismanagement of previous biomass schemes that sought to incentivise the cultivation of Miscanthus in particular. However, the incentivisation took place without having a mature biomass market in place to purchase the feedstock.

Exchequer Costs

There were previously grants for the planting and establishment of willow and Miscanthus but these have been discontinued and are unlikely to re-emerge in the short term. For all biomass measures, including woodchip, the Support Scheme for renewable heat has set aside a €7 million budget.

33. Energy Savings Measures

Pathway	Abatement in 2025 (ktCO₂e yr⁻¹)	Abatement in 2030 (ktCO₂e yr⁻¹)	Mean abatement (ktCO₂e yr⁻¹)	Cost 2025 (million €)	Cost 2030 (million €)	€ per tonne CO₂e
Pathway 1& 2	19.13	76.53	29.47	-12.89	-117	-1531
Range	9.56 to 19.13	38.26 to 76.53	14.73 to 29.47	-12.89 to 5.42	-27.53 to -117	-359 to -1531

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.

Emissions and uptake assumptions

The emission reductions per unit are derived from Upton et al. (2015) and are shown in Table 24. Uptake rates were as follows: Plate cooler – 50% of dairy farms, VSD – 25% of dairy farms, Heat recovery and Solar PV – 12.5%.

Cumulative GHG emissions reductions during the whole lifetime of each measure were 76.3, 25.5, 17.05 and 57.2 tCO_2-e per unit for plate coolers, VSD, heat recovery and solar PV respectively. This resulted in a 29.5 ktCO_2-e reduction between 2021 and 2030 assuming linear uptake of measures by 2030 (Upton et al. 2015).

Cost Assumptions

Two cost scenarios were examined – electricity at 20c per kWh and 40c per kWh, with the initial annualized cost per unit at €2500 (Plate cooler), €3000 (VSD) and €6000 for both heat recovery and solar PV.

Sensitivity Analysis

The main sources of uncertainty are uptake rate and energy costs

Inventory Incorporation

This measure would be accounted in the national inventory via reduced energy usage.

Barriers to Uptake

The principal barrier to heat recovery systems and solar PV in particular are the upfront cost and the variable energy costs. If high energy prices are sustained, all measures should be profitable over a 15 year period.

Exchequer Costs

Plate coolers, heat recovery systems and Solar PV are covered under the TAMS scheme, while VSD's are grant-aided by SEAI. Under TAMS, plate coolers and Heat Recovery is grant-aided to 40% (60% for young farmers) while Solar PV is grant-aided to 60% of the cost up to a value of €90k per farm. VSD's are grant-aided at 50% of cost up to €5000 per unit. Assuming the above uptake rates, the total exchequer cost would be €30.49M.

Table 7. 16: *Exchequer costs associated with energy saving & generation*

Measure	Mean cost	Grant Aid	Exchequer
solar	10000	60%	11,724,000
VSD	3000	50%	5,864,250
Plate cooler	2500	40%	7,819,000
Heat recovery system	6500	40%	5,082,350

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9. Appendices

Appendix 1. Detailed Tables associated with Mitigation Options

Table A1.1: Overview of Modelling Assumptions Used and Results for Dairy EBI

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Population	1000 head	1554.9	1599.8	1616.6	1608.6	1608.9	1623.7	1643.4	1662.9	1679.3	1691.8	1629.0
Population	1000 head	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3	312.0
Milk per cow	kg/hd/yr	5,537	5,586	5,633	5,679	5,725	5,756	5,788	5,818	5,847	5,874	5724.3
Milk Solids per cow	kg/hd/yr	462	465.55	469.06	472.54	476.01	478.36	480.79	483.06	485.26	487.35	476.0
Total Milk Production	Mt milk/yr	8.61	8.94	9.11	9.14	9.21	9.35	9.51	9.67	9.82	9.94	9.3
Total Milk Solids	Kt MS/yr	718.36	744.76	758.26	760.14	765.85	776.72	790.13	803.26	814.90	824.53	775.7
Enteric Fermentation EF	Kg CH4/yr	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5	126.8
Enteric Fermentation EF	Kg CH4/yr	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9
Manure Methane EF	Kg CH4/yr	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Manure Methane EF	Kg CH4/yr	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.5
Total Enteric Methane	Gg CH4/yr	191.48	198.29	201.67	201.99	203.34	206.54	210.41	214.28	217.81	220.86	206.7
Total Enteric Methane	Gg CH4/yr	16.29	16.84	16.74	16.75	16.93	17.17	17.40	17.60	17.75	17.86	17.1
Total Manure Methane	Gg CH4/yr	17.72	18.23	18.42	18.33	18.34	18.51	18.73	18.95	19.14	19.28	18.6

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Manure Methane	Gg CH4/yr	1.33	1.37	1.36	1.36	1.38	1.40	1.42	1.43	1.45	1.45	1.4
Total Methane - GWP 28	Mt CO2e/yr	6.35	6.57	6.67	6.68	6.72	6.82	6.94	7.06	7.17	7.26	6.8
N excretion per animal	kg N/hd/yr	111.0	112.2	113.4	114.7	115.9	117.2	118.5	119.8	121.1	122.4	116.6
N excretion per animal	kg N/hd/yr	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4
Total N excretion	t N/yr	172535	179465	183344	184451	186514	190301	194727	199198	203384	207155	190107
Total N excretion	t N/yr	21498	22216	22089	22099	22337	22650	22959	23220	23418	23563	22605
Slurry housing Period	proportion of year	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Slurry housing Period	proportion of year	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Solid manure housing period	proportion of year	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Solid manure housing period	proportion of year	0	0	0	0	0	0	0	0	0	0	0.00
N excretion in slurry system	t N/yr	50035	52045	53170	53491	54089	55187	56471	57768	58981	60075	55131
N excretion in slurry system	t N/yr	7524	7776	7731	7735	7818	7928	8036	8127	8196	8247	7912
N excretion in solid manure system	t N/yr	3451	3589	3667	3689	3730	3806	3895	3984	4068	4143	3802

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
N excretion in solid manure system	t N/yr	0	0	0	0	0	0	0	0	0	0	0
N excretion at pasture	t N/yr	119049	123831	126508	127271	128694	131308	134362	137447	140335	142937	131174
N excretion at pasture	t N/yr	13973	14441	14358	14364	14519	14723	14923	15093	15222	15316	14693
Grazing NH3 EF	kg NH3/kg TAN	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Slurry housing & storage NH3 EF	kg NH3/kg TAN	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.28
Solid manure housing NH3 EF	kg NH3/kg TAN	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.46
Slurry spreading NH3 EF	kg NH3/kg TAN	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Solid manure spread NH3 EF	kg NH3/kg TAN	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
NH3 from grazing	t NH3-N/yr	7981	8296	8452	8498	8593	8762	8957	9152	9333	9495	8752
NH3 from slurry house/store	t NH3-N/yr	16059	16690	16991	17082	17272	17609	17997	18385	18743	19062	17589
NH3 from manure house/store	t NH3-N/yr	1584	1647	1683	1693	1712	1747	1788	1829	1867	1902	1745
NH3 from slurry spreading	t NH3-N/yr	14110	14664	14929	15009	15176	15472	15813	16153	16468	16748	15454

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
NH3 from solid manure spreading	t NH3-N/yr	1269	1320	1349	1357	1372	1400	1433	1466	1496	1524	1399
Indirect N2O deposition EF3	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Indirect N2O from deposition	Gg N2O/yr	**0.410**	**0.426**	**0.434**	**0.436**	**0.441**	**0.450**	**0.460**	**0.470**	**0.479**	**0.487**	0
Grazing Urine N2O EF2	kg N2O-N/kg N	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0
Grazing Dung N2O EF2	kg N2O-N/kg N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0
Proportion of urine N		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1
Proportion of dung N		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0
Slurry N2O EF	kg N2O-N/kg N	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0
Solid manure N2O EF	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Organic manure N2O spreading EF1	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
N2O Grazing	Gg N2O/yr	0.975	1.014	1.033	1.038	1.050	1.071	1.095	1.118	1.141	1.160	1
N2O slurry systems	Gg N2O/yr	0.115	0.120	0.122	0.122	0.124	0.126	0.129	0.132	0.134	0.137	0
N2O solid manure systems	Gg N2O/yr	0.035	0.036	0.037	0.037	0.037	0.038	0.039	0.040	0.041	0.041	0
N2O slurry/manure spreading	Gg N2O/yr	0.610	0.634	0.646	0.649	0.656	0.669	0.684	0.699	0.712	0.725	1

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Direct N2O	Gg N2O/yr	**1.735**	**1.803**	**1.837**	**1.847**	**1.868**	**1.904**	**1.947**	**1.989**	**2.028**	**2.063**	2
N available for leaching	t N/yr	153028	159063	162029	162911	164725	167961	171698	175434	178895	181986	167773
Fraction of Leached N		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0
EF4 - Leached N N2O EF	kg N2O/Kg N applied	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Indirect N2O from leaching	Gg N2O/yr	**0.115**	**0.119**	**0.122**	**0.122**	**0.124**	**0.126**	**0.129**	**0.132**	**0.134**	**0.136**	0
Total N2O	Gg N2O/yr	2.260	2.349	2.393	2.406	2.432	2.480	2.535	2.590	2.641	2.687	2
Total N2O	Mt CO2e/yr	0.941	0.978	0.996	1.002	1.013	1.033	1.056	1.079	1.100	1.119	1
Total GHG	Mt CO2e/yr	**7.292**	**7.551**	**7.666**	**7.678**	**7.732**	**7.854**	**7.998**	**8.142**	**8.272**	**8.384**	8
Higher EBI		**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**230**	**240**	
Population	1000 head	1554.9	1599.8	1616.6	1608.6	1608.9	1623.7	1643.4	1662.9	1679.3	1691.8	1629
%		19.08	19.08	19.08	19.08	19.08	19.08	19.08	19.08	19.08	19.08	19
Population	1000 head	296.7	305.2	308.4	306.9	307.0	309.8	313.6	317.3	320.4	322.8	311
Milk per cow	kg/hd/yr	5,785	5,837	5,888	5,939	5,990	6,041	6,093	6,144	6,195	6,297	6021
Total Milk Production	Mt milk/yr	9.00	9.34	9.52	9.55	9.64	9.81	10.01	10.22	10.40	10.65	10
		3.54	3.55	3.5105	3.529	3.5475	3.566	3.5845	3.603	3.6215	3.64	4
		4.23	4.28	4.2136	4.2478	4.282	4.3162	4.3504	4.3846	4.4188	4.453	4
Total Milk Solids	Kt MS/yr	698.96	731.09	735.17	742.95	754.57	773.20	794.48	816.02	836.45	862.19	775
Delta EBI		37	47	57	67	77	87	97	107	117	127	82
Overestimate in methane	%	1.184	1.504	1.824	2.144	2.464	2.784	3.104	3.424	3.744	4.064	3

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Enteric Fermentation EF	Kg CH4/yr	121.7	122.1	122.5	122.9	123.3	123.7	124.1	124.5	124.8	125.2	123
Enteric Fermentation EF	Kg CH4/yr	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	55
Manure Methane EF	Kg CH4/yr	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11
Manure Methane EF	Kg CH4/yr	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4
Total Enteric Methane	Gg CH4/yr	189.22	195.31	198.00	197.66	198.33	200.79	203.88	206.94	209.65	211.88	201
Total Enteric Methane	Gg CH4/yr	16.29	16.76	16.93	16.85	16.85	17.01	17.21	17.42	17.59	17.72	17
Total Manure Methane	Gg CH4/yr	17.72	18.23	18.42	18.33	18.34	18.51	18.73	18.95	19.14	19.28	19
Total Manure Methane	Gg CH4/yr	1.33	1.36	1.38	1.37	1.37	1.39	1.40	1.42	1.43	1.44	1
Total Methane - GWP 28	Mt CO2e/yr	6.29	6.49	6.57	6.56	6.58	6.66	6.75	6.85	6.94	7.01	7
Absolute Methane Reduction	**kt CO2e/yr**	**63.62**	**85.91**	**97.16**	**118.16**	**142.55**	**165.77**	**188.47**	**210.86**	**233.09**	**255.42**	156
EBI	€ hd-1	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**230**	**240**	195
	000 euro	**€111,953**	**€147,178**	**€181,055**	**€212,338**	**€244,555**	**€279,280**	**€315,534**	**€352,525**	**€389,603**	**€426,345**	266037
Abatement Cost	€ t-1CO2e	**-€746.35**	**-€919.86**	**-€1,065.03**	**-€1,179.66**	**-€1,287.13**	**-€1,396.40**	**-€1,502.55**	**-€1,602.39**	**-€1,693.93**	**-€1,776.4**	-1317
N excretion per animal	kg N/hd/yr	111.0	112.2	113.4	114.7	115.9	117.2	118.5	119.8	121.1	122.4	117
N excretion per animal	kg N/hd/yr	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total N excretion	t N/yr	172535	179465	183344	184451	186514	190301	194727	199198	203384	207155	190107
Total N excretion	t N/yr	21491	22112	22344	22234	22238	22443	22715	22984	23211	23384	22516
Slurry housing Period	proportion of year	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0
Slurry housing Period	proportion of year	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0
Solid manure housing period	proportion of year	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0
Solid manure housing period	proportion of year	0	0	0	0	0	0	0	0	0	0	0
N excretion in slurry system	t N/yr	50035	52045	53170	53491	54089	55187	56471	57768	58981	60075	55131
N excretion in slurry system	t N/yr	7522	7739	7820	7782	7783	7855	7950	8044	8124	8184	7880
N excretion in solid manure system	t N/yr	3451	3589	3667	3689	3730	3806	3895	3984	4068	4143	3802
N excretion in solid manure system	t N/yr	0	0	0	0	0	0	0	0	0	0	0
N excretion at pasture	t N/yr	119049	123831	126508	127271	128694	131308	134362	137447	140335	142937	131174
N excretion at pasture	t N/yr	13969	14372	14523	14452	14455	14588	14765	14939	15087	15200	14635
Grazing NH3 EF	kg NH3/kg TAN	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0
Slurry housing & storage NH3 EF	kg NH3/kg TAN	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Solid manure housing NH3 EF	kg NH3/kg TAN	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0
Slurry spreading NH3 EF	kg NH3/kg TAN	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0
Solid manure spread NH3 EF	kg NH3/kg TAN	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	1
NH3 from grazing	t NH3-N/yr	7981	8292	8462	8503	8589	8754	8948	9143	9325	9488	8749
NH3 from slurry house/store	t NH3-N/yr	16058	16680	17016	17095	17262	17589	17973	18361	18722	19044	17580
NH3 from manure house/store	t NH3-N/yr	1584	1647	1683	1693	1712	1747	1788	1829	1867	1902	1745
NH3 from slurry spreading	t NH3-N/yr	14110	14655	14951	15020	15167	15454	15792	16133	16450	16733	15447
NH3 from solid manure spreading	t NH3-N/yr	1269.4	1320.4	1349.0	1357.1	1372.3	1400.2	1432.7	1465.6	1496.4	1524.2	1399
Indirect N2O deposition EF3	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Indirect N2O from deposition	Gg N2O/yr	0.410	0.426	0.435	0.437	0.441	0.449	0.459	0.469	0.479	0.487	0
Grazing Urine N2O EF2	kg N2O-N/kg N	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0
Grazing Dung N2O EF2	kg N2O-N/kg N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0

Parameter	**Units**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Proportion of urine N		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1
Proportion of dung N		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0
Slurry N2O EF	kg N2O-N/kg N	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0
Solid manure N2O EF	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Organic manure N2O spreading EF1	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
N2O Grazing	Gg N2O/yr	0.975	1.013	1.034	1.039	1.050	1.070	1.093	1.117	1.140	1.159	1.069
N2O slurry systems	Gg N2O/yr	0.115	0.120	0.122	0.123	0.124	0.126	0.129	0.132	0.134	0.137	0.126
N2O solid manure systems	Gg N2O/yr	0.035	0.036	0.037	0.037	0.037	0.038	0.039	0.040	0.041	0.041	0.038
N2O slurry/manure spreading	Gg N2O/yr	0.610	0.634	0.647	0.650	0.656	0.668	0.683	0.698	0.712	0.724	0.668
Total Direct N2O	Gg N2O/yr	**1.735**	**1.803**	**1.839**	**1.848**	**1.867**	**1.902**	**1.944**	**1.987**	**2.026**	**2.061**	1.901
N available for leaching	t N/yr	153024	158981	162227	163016	164648	167800	171508	175250	178734	181847	167704
Fraction of Leached N		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.100
EF4 - Leached N N2O EF	kg N2O/Kg N applied	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.008
Indirect N2O from leaching	Gg N2O/yr	**0.115**	**0.119**	**0.122**	**0.122**	**0.123**	**0.126**	**0.129**	**0.131**	**0.134**	**0.136**	0.126
Total N2O	Gg N2O/yr	2.260	2.348	2.396	2.407	2.431	2.478	2.532	2.587	2.639	2.685	2.476

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total N2O	Mt CO2e/yr	0.941	0.978	0.998	1.002	1.012	1.032	1.055	1.077	1.099	1.118	1.031
Total GHG	Mt CO2e/yr	**7.23**	**7.46**	**7.57**	**7.56**	**7.59**	**7.69**	**7.81**	**7.93**	**8.04**	**8.13**	7.70
Lower EBI												
Population	1000 head	1554	1604	1609	1616	1633	1651	1680	1721	1760	1810	1664
Population	1000 head	298.68	308.29	309.25	310.60	313.86	317.32	322.90	330.78	338.27	347.88	320
Milk per cow	kg/hd/yr	5,537	5,586	5,603	5,649	5,725	5,756	5,788	5,818	5,847	5,874	5718
Milk Solids per cow	kg/hd/yr	450	455.5	457.1	459.5	462.0	468.4	472.8	474.1	475.3	476.4	465
Total Milk Production	Mt milk/yr	8.6	9.0	9.0	9.1	9.3	9.5	9.7	10.0	10.3	10.6	10
Total Milk Solids	Kt MS/yr	698.5	730.6	735.4	742.6	754.5	773.3	794.3	815.9	836.5	862.2	774
Enteric Fermentation EF	Kg CH4/yr	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5	126.8
Enteric Fermentation EF	Kg CH4/yr	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9
Manure Methane EF	Kg CH4/yr	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Manure Methane EF	Kg CH4/yr	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Total Enteric Methane	Gg CH4/yr	191.4	198.8	200.7	202.9	206.4	210.0	215.1	221.8	228.3	236.3	211.2
Total Enteric Methane	Gg CH4/yr	16.40	16.93	16.98	17.05	17.23	17.42	17.73	18.16	18.57	19.10	17.56
Total Manure Methane	Gg CH4/yr	17.71	18.28	18.34	18.42	18.61	18.82	19.15	19.61	20.06	20.63	18.96
Total Manure Methane	Gg CH4/yr	1.34	1.38	1.38	1.39	1.40	1.42	1.44	1.48	1.51	1.56	1.43

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Methane - GWP 28	Mt CO2e/yr	6.35	6.59	6.65	6.71	6.82	6.93	7.10	7.31	7.52	7.77	6.98
N excretion per animal	kg N/hd/yr	111.0	112.2	113.4	114.7	115.9	117.2	118.5	119.8	121.1	122.4	116.6
N excretion per animal	kg N/hd/yr	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4
Total N excretion	t N/yr	172435	179941	182487	185297	189306	193498	199063	206164	213155	221622	194297
Total N excretion	t N/yr	21637	22333	22402	22500	22737	22987	23391	23962	24505	25201	23165
Slurry housing Period	proportion of year	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0
Slurry housing Period	proportion of year	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0
Solid manure housing period	proportion of year	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0
Solid manure housing period	proportion of year	0	0	0	0	0	0	0	0	0	0	0
N excretion in slurry system	t N/yr	50006	52183	52921	53736	54899	56114	57728	59788	61815	64270	56346
N excretion in slurry system	t N/yr	7573	7816	7841	7875	7958	8046	8187	8387	8577	8820	8108
N excretion in solid manure system	t N/yr	3449	3599	3650	3706	3786	3870	3981	4123	4263	4432	3886
N excretion in solid manure system	t N/yr	0	0	0	0	0	0	0	0	0	0	0

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
N excretion at pasture	t N/yr	118980	124159	125916	127855	130621	133514	137353	142253	147077	152919	134065
N excretion at pasture	t N/yr	14064	14516	14562	14625	14779	14942	15204	15575	15928	16381	15057
Grazing NH3 EF	kg NH3/kg TAN	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0
Slurry housing & storage NH3 EF	kg NH3/kg TAN	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279	0
Solid manure housing NH3 EF	kg NH3/kg TAN	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0.459	0
Slurry spreading NH3 EF	kg NH3/kg TAN	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0
Solid manure spread NH3 EF	kg NH3/kg TAN	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	1
NH3 from grazing	t NH3-N/yr	7983	8321	8429	8549	8724	8907	9153	9470	9780	10158	8947
NH3 from slurry house/store	t NH3-N/yr	16065	16740	16953	17189	17537	17901	18390	19021	19639	20392	17983
NH3 from manure house/store	t NH3-N/yr	1583	1652	1675	1701	1738	1776	1827	1893	1957	2034	1784
NH3 from slurry spreading	t NH3-N/yr	14115	14708	14895	15103	15409	15728	16158	16712	17256	17917	15800
NH3 from solid manure spreading	t NH3-N/yr	1269	1324	1343	1363	1393	1424	1465	1517	1568	1631	1430

Parameter	Units	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Indirect N2O deposition EF3	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Indirect N2O from deposition	Gg N2O/yr	**0.410**	**0.427**	**0.433**	**0.439**	**0.448**	**0.457**	**0.470**	**0.486**	**0.502**	**0.521**	0.46
Grazing Urine N2O EF2	kg N2O-N/kg N	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.01
Grazing Dung N2O EF2	kg N2O-N/kg N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.00
Proportion of urine N		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.60
Proportion of dung N		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.40
Slurry N2O EF	kg N2O-N/kg N	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.00
Solid manure N2O EF	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Organic manure N2O spreading EF1	kg N2O-N/kg N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
N2O Grazing	Gg N2O/yr	0.975	1.017	1.030	1.045	1.066	1.088	1.119	1.157	1.195	1.241	1.093
N2O slurry systems	Gg N2O/yr	0.115	0.120	0.122	0.123	0.126	0.128	0.132	0.136	0.141	0.146	0.129
N2O solid manure systems	Gg N2O/yr	0.034	0.036	0.036	0.037	0.038	0.039	0.040	0.041	0.043	0.044	0.039
N2O slurry/manure spreading	Gg N2O/yr	0.610	0.636	0.644	0.653	0.666	0.680	0.699	0.723	0.747	0.775	0.683
Total Direct N2O	Gg N2O/yr	**1.735**	**1.809**	**1.832**	**1.858**	**1.896**	**1.936**	**1.989**	**2.058**	**2.125**	**2.207**	1.945

Parameter	**Units**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
N available for leaching		153058	159529	161595	163891	167242	170749	175459	181514	187459	194690	171519
Fraction of Leached N	t N/yr	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0
EF4 - Leached N N2O EF	kg N2O/Kg N applied	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.008
Indirect N2O from leaching	Gg N2O/yr	**0.1148**	**0.1196**	**0.1212**	**0.1229**	**0.1254**	**0.1281**	**0.1316**	**0.1361**	**0.1406**	**0.1460**	0.129
Total N2O	Gg N2O/yr	2.26	2.36	2.39	2.42	2.47	2.52	2.59	2.68	2.77	2.87	2.533
Total N2O	Mt CO2e/yr	0.94	0.98	0.99	1.01	1.03	1.05	1.08	1.12	1.15	1.20	1.055
Total GHG	Mt CO2e/yr	7.29	7.57	7.64	7.72	7.85	7.98	8.17	8.42	8.67	8.97	8.030
Reduction relative to high EBI	**kt CO2e/yr**	**63.650**	**108.031**	**71.659**	**161.054**	**260.626**	**297.512**	**365.551**	**494.772**	**630.415**	**841.58**	**329.48**
Abatement Cost	**€ t-1CO2e**	**-€1,758.89**	**-€1,362.37**	**-€2,526.61**	**-€1,318.43**	**-€938.34**	**-€938.72**	**-€863.17**	**-€712.50**	**-€618.01**	**-€506.60**	**-€1,154.36**

Table A1.2: Overview of Modelling Assumptions Used and Results for Replacement and Terminal Index

a) Replacement Index

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
No. suckler cows ('000)	899.5	863.7	832.7	804.9	777.8	750.6	722.9	694.6	666.0	637.4
Replacement index – Pathway 1										
Replacement index increase per year (€)	3	3	3	3	3	3	3	3	3	3
CO2e reduction per € increase in RI (kg)	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495
Total € benefit (€,000)	2698.5	2591.2	2498.1	2414.6	2333.5	2251.8	2168.7	2083.9	1998.0	1912.2
Total CO2 benefit (kt)	3.6	3.5	3.4	3.3	3.1	3.0	2.9	2.8	2.7	2.6
Total abatement (kt CO2e)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
2023 abatement contribution			3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
2024 abatement contribution				3.3	3.3	3.3	3.3	3.3	3.3	3.3
2025 abatement contribution					3.1	3.1	3.1	3.1	3.1	3.1
2026 abatement contribution						3.0	3.0	3.0	3.0	3.0
2027 abatement contribution							2.9	2.9	2.9	2.9
2028 abatement contribution								2.8	2.8	2.8
2029 abatement contribution									2.7	2.7
2030 abatement contribution										2.6
Total compared to 2021		3.5	6.9	10.1	13.3	16.3	19.2	22.1	24.7	27.3
MAC (€/kt)	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0
Total CO2e 2021-2025 (kt)	**33.8**									
Total CO2e 2021-2030 (kt)	**143.5**									
Replacement index – Pathway 2										
Replacement index increase per year (€)	5	5	5	5	5	5	5	5	5	5

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CO2e reduction per € increase in RI (kg)	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495	1.3495
Total € benefit (€,000)	4497.6	4318.7	4163.6	4024.4	3889.1	3753.0	3614.5	3473.2	3329.9	3187.0
Total CO2 benefit (kt)	6.1	5.8	5.6	5.4	5.2	5.1	4.9	4.7	4.5	4.3
Total abatement (kt CO2e)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
2023 abatement contribution			5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
2024 abatement contribution				5.4	5.4	5.4	5.4	5.4	5.4	5.4
2025 abatement contribution					5.2	5.2	5.2	5.2	5.2	5.2
2026 abatement contribution						5.1	5.1	5.1	5.1	5.1
2027 abatement contribution							4.9	4.9	4.9	4.9
2028 abatement contribution								4.7	4.7	4.7
2029 abatement contribution									4.5	4.5
2030 abatement contribution										4.3
Total Annual Abatement		5.8	11.4	16.9	22.1	27.2	32.1	36.8	41.2	45.6
MAC (€/kt)		-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0	-741.0
Total CO2e 2021-2025 (kt)	**56.3**									
Total CO2e 2021-2030 (kt)	**239.1**									

b) Terminal Index

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Prime kill ('000)	1,257.9	1,154.8	1,137.3	1,151.8	1,150.8	1,138.5	1,134.3	1,129.4	1,124.3	1,119.0
Numbers by group										
EM suckler heifers	36.8	35.9	34.5	33.9	32.5	31.4	30.3	29.3	28.3	27.2
LM suckler heifers	205.1	199.8	192.2	188.5	181.0	174.5	168.7	163.0	157.3	151.5
EM suckler steers	48.1	46.8	45.0	44.2	42.4	40.9	39.5	38.2	36.9	35.5
LM suckler steers	214.1	208.5	200.6	196.8	189.0	182.2	176.1	170.2	164.3	158.2
EM suckler bulls	7.0	6.8	6.5	6.4	6.1	5.9	5.7	5.5	5.3	5.1
LM suckler bulls	65.7	64.0	61.6	60.4	58.0	55.9	54.0	52.2	50.4	48.5
EM dairy heifers	167.9	173.3	177.8	181.2	182.2	183.1	185.1	187.5	189.8	192.2
LM dairy heifers	38.3	39.5	40.5	41.3	41.5	41.8	42.2	42.8	43.3	43.8
Dairy heifers	24.8	25.6	26.2	26.7	26.9	27.0	27.3	27.7	28.0	28.4
EM dairy steers	194.1	200.3	205.5	209.4	210.6	211.6	213.9	216.7	219.4	222.1
LM dairy steers	49.2	50.8	52.1	53.1	53.4	53.6	54.2	54.9	55.6	56.3
Dairy steers	160.0	165.1	169.4	172.7	173.6	174.5	176.4	178.7	180.9	183.1
LM dairy bulls	11.8	12.2	12.5	12.8	12.8	12.9	13.0	13.2	13.4	13.5
EM dairy bulls	6.7	6.9	7.1	7.2	7.2	7.3	7.4	7.5	7.5	7.6
Dairy bulls	34.4	35.5	36.4	37.1	37.3	37.5	37.9	38.4	38.8	39.3
Terminal index - Pathway 1										
Terminal index increase per year (€)										
Beef x Beef	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Beef x Dairy	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Dairy x Dairy	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO2e reduction per € increase in TI (kg)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
€ benefit by group (€,000)										
EM suckler heifers	84.7	82.5	79.4	77.9	74.8	72.1	69.7	67.4	65.0	62.6
LM suckler heifers	471.6	459.4	442.0	433.7	416.4	401.5	388.0	375.0	361.9	348.5
EM suckler steers	110.5	107.7	103.6	101.6	97.6	94.1	90.9	87.9	84.8	81.7
LM suckler steers	492.4	479.7	461.5	452.7	434.7	419.1	405.1	391.5	377.8	363.8
EM suckler bulls	16.0	15.6	15.0	14.7	14.1	13.6	13.2	12.7	12.3	11.8

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LM suckler bulls	151.0	147.1	141.6	138.9	133.4	128.6	124.3	120.1	115.9	111.6
EM dairy heifers	251.9	259.9	266.7	271.8	273.3	274.6	277.6	281.2	284.8	288.2
LM dairy heifers	57.5	59.3	60.8	62.0	62.3	62.6	63.3	64.1	64.9	65.7
Dairy heifers	2.5	2.6	2.6	2.7	2.7	2.7	2.7	2.8	2.8	2.8
EM dairy steers	291.2	300.4	308.2	314.1	315.9	317.4	320.9	325.0	329.1	333.1
LM dairy steers	73.8	76.1	78.1	79.6	80.0	80.4	81.3	82.4	83.4	84.4
Dairy steers	16.0	16.5	16.9	17.3	17.4	17.4	17.6	17.9	18.1	18.3
LM dairy bulls	17.7	18.3	18.8	19.1	19.2	19.3	19.5	19.8	20.0	20.3
EM dairy bulls	10.0	10.3	10.6	10.8	10.9	10.9	11.0	11.2	11.3	11.5
Dairy bulls	3.4	3.5	3.6	3.7	3.7	3.7	3.8	3.8	3.9	3.9
Total € benefit (€,000)	2050.3	2039.0	2009.5	2000.6	1956.4	1918.2	1889.2	1862.7	1836.0	1808.4
Abatement by group (kt CO2e)										
EM suckler heifers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LM suckler heifers	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
EM suckler steers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LM suckler steers	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
EM suckler bulls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LM suckler bulls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EM dairy heifers	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LM dairy heifers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dairy heifers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EM dairy steers	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LM dairy steers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dairy steers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LM dairy bulls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EM dairy bulls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dairy bulls	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total abatement (kt CO2e)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total abatement (kt CO2e)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2023 abatement contribution			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2024 abatement contribution				0.1	0.1	0.1	0.1	0.1	0.1	0.1
2025 abatement contribution					0.1	0.1	0.1	0.1	0.1	0.1
2026 abatement contribution						0.1	0.1	0.1	0.1	0.1
2027 abatement contribution							0.1	0.1	0.1	0.1
2028 abatement contribution								0.1	0.1	0.1
2029 abatement contribution									0.1	0.1
2030 abatement contribution										0.1
Total Annual Abatement ($tCO_2e\ yr^{-1}$)		0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5
MAC (€/kt)	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6
Total CO2e 2021-2025 (kt)	**0.6**									
Total CO2e 2021-2030 (kt)	**2.6**									
Terminal index - Pathway 2										
Terminal index increase per year (€)										
Beef x Beef	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Beef x Dairy	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Dairy x Dairy	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO2e reduction per € increase in TI (kg)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
€ benefit by group (€,000)										
EM suckler heifers	184.2	179.4	172.6	169.3	162.6	156.8	151.5	146.4	141.3	136.1
LM suckler heifers	1025.3	998.8	961.0	942.7	905.2	872.7	843.5	815.2	786.7	757.6
EM suckler steers	240.3	234.1	225.2	220.9	212.2	204.5	197.7	191.1	184.4	177.6
LM suckler steers	1070.4	1042.7	1003.2	984.2	945.1	911.1	880.7	851.1	821.3	791.0
EM suckler bulls	34.8	33.9	32.6	32.0	30.7	29.6	28.6	27.7	26.7	25.7
LM suckler bulls	328.4	319.9	307.8	301.9	289.9	279.5	270.2	261.1	251.9	242.6
EM dairy heifers	503.8	519.8	533.3	543.5	546.5	549.3	555.3	562.4	569.5	576.5
LM dairy heifers	114.9	118.6	121.6	124.0	124.6	125.3	126.6	128.3	129.9	131.5
Dairy heifers	2.5	2.6	2.6	2.7	2.7	2.7	2.7	2.8	2.8	2.8

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
EM dairy steers	582.3	600.8	616.4	628.2	631.7	634.9	641.8	650.0	658.3	666.3
LM dairy steers	147.6	152.3	156.2	159.2	160.1	160.9	162.7	164.7	166.8	168.9
Dairy steers	16.0	16.5	16.9	17.3	17.4	17.4	17.6	17.9	18.1	18.3
LM dairy bulls	35.5	36.6	37.5	38.3	38.5	38.7	39.1	39.6	40.1	40.6
EM dairy bulls	20.0	20.7	21.2	21.6	21.7	21.8	22.1	22.4	22.6	22.9
Dairy bulls	3.4	3.5	3.6	3.7	3.7	3.7	3.8	3.8	3.9	3.9
Total € benefit (€,000)	4309.4	4280.1	4212.0	4189.6	4092.7	4008.9	3943.9	3884.4	3824.3	3762.3
Abatement by group (kt CO2e)										
EM suckler heifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM suckler heifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EM suckler steers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM suckler steers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EM suckler bulls	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM suckler bulls	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EM dairy heifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM dairy heifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy heifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EM dairy steers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM dairy steers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy steers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM dairy bulls	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EM dairy bulls	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy bulls	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total abatement (kt CO2e)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total abatement (kt CO2e)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2023 abatement contribution			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2024 abatement contribution				0.1	0.1	0.1	0.1	0.1	0.1	0.1
2025 abatement contribution					0.1	0.1	0.1	0.1	0.1	0.1
2026 abatement contribution						0.1	0.1	0.1	0.1	0.1

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2027 abatement contribution							0.1	0.1	0.1	0.1
2028 abatement contribution								0.1	0.1	0.1
2029 abatement contribution									0.1	0.1
2030 abatement contribution										0.1
Total Annual Abatement (tCO_2e yr^{-1})		0.1	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.1
MAC (€/kt)	5.5	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6	-33519.6
Total CO2e 2021-2025 (kt)	**1.3**									
Total CO2e 2021-2030 (kt)	**5.5**									

Table A1.3: Overview of Modelling Assumptions Used and Results for Animal Health

Measure	**ktCO2-e abated**	**Total Cost**	**cost euro per tonne basis**								
Vaccination Pneumonia	7.839	-€1,550,554	-€197.80								
Milk routine	64.32	-€11,686,944	-€181.70								
Vaccination IBR	185.59	-€20,275,708	-€109.25								
Johnes hygiene and Colo management	192.96	-€18,196,128	-€94.30								
Dry cow therapy (mastitis)	57.62	-€3,379,413	-€58.65								
Johnes buying policy	205.69	-€12,063,719	-€58.65								
Fluke treatment	245.89	-€11,310,940	-€46.00								
IBR Fencing/purchase policy	151.42	-€1,218,931	-€8.05								
Johnes vacc	111.89	-€772,041	-€6.90								
Pnuemonia colostrum intake	8.04	-€55,476	-€6.90								
IBR Carrier id	154.77	-€711,942	-€4.60								
Samonella hygiene	55.61	-€63,952	-€1.15								
Samonella vacc	55.61	€0	€0.00								
Samonella vector control	51.59	€177,986	€3.45								
Fluke - grazing management	188.27	€2,381,616	€12.65								

Infertility- fixed time AI	90.45	€1,664,280	€18.40								
Pnuemonia - building vent, stock density	6.03	€450,743	€74.75								
Infertility - nutrition	58.96	€7,187,224	€121.90								
Infertility - tail paint	44.89	€6,194,820	€138.00								
Lameness - cow hardiness	18.76	€3,300,822	€175.95								
Scour - cow comfort	0.67	€144,854	€216.20								
Lameness - mobility management	30.15	€7,211,880	€239.20								
Scour - prophylactic therapy	1.005	€265,823	€264.50								
Mastitis nutrition	29.815	€9,909,015	€332.35								
Scour - vacc	0.938	€495,123	€527.85								
Mastitis Housing/milking	16.08	€8,728,224	€542.80								
Lameness - slat mats	20.1	€16,758,375	€833.75								
Total Abatement (100% healthy)	2055	-€16,414,963	-€7.99								
Pathway 1											
20% move to healthy		***2021***	***2022***	***2023***	***2024***	***2025***	***2026***	***2027***	***2028***	***2029***	***2030***
Emission saving	$ktCO_2e$	41.10	82.20	123.30	164.40	205.50	246.60	287.70	328.80	369.90	411.0
Total cost	Euro	-€328,299	-€656,598	-€984,897	-€1,313,196	-€1,641,495	-€1,969,794	-€2,298,093	-€2,626,392	-€2,954,691	-€3,282,993
Abatement Cost	€ $t^{-1}CO_2e$	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99
Pathway 2											

40% move to healthy		*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
Emission saving	$ktCO_2e$	82.20	164.40	246.60	328.80	411.00	493.20	575.40	657.60	739.80	822.0
Total cost	Euro	-€656,599	-€1,313,198	-€1,969,797	-€2,626,396	-€3,282,995	-€3,939,594	-€4,596,193	-€5,252,792	-€5,909,391	-€6,565,985
Abatement Cost	€ $t^{-1}CO_2e$	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99	-€7.99

Table A1.4: Overview of Modelling Assumptions Used and Results for Extended Grazing

	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
Dairy Cows	000 head	1,551.1	1,554.9	1,599.8	1,616.6	1,608.6	1,608.9	1,623.7	643.4	1,662.9	1,679.3	1,691.8	
Other Cows	000 head	916.9	915.0	892.8	847.8	802.6	764.4	735.1	709.0	682.9	657.7	632.0	
Cattle < 1 yrs - male	000 head	1,027.9	1,027.9	1,059.5	1,038.4	1,062.8	1,072.7	1,062.7	1,050.1	1,039.1	1,032.4	1,027.9	
Cattle 1 - 2 yrs - male	000 head	864.3	864.3	797.6	781.7	800.0	807.4	799.9	790.4	782.2	777.1	773.7	
Cattle > 2 yrs - male	000 head	363.6	363.6	373.4	366.0	374.5	378.0	374.5	370.1	366.2	363.8	362.2	
Cattle < 1 yrs - female	000 head	1,118.0	1,118.0	1,070.1	1,049.0	1,080.9	1,093.0	1,078.7	1,060.9	1,043.2	1,036.6	1,026.3	
Cattle 1 - 2 yrs - female	000 head	661.8	733.9	640.4	627.7	646.8	654.1	645.5	634.9	624.3	620.3	614.2	
Cattle > 2 yrs - female	000 head	248.2	225.9	204.3	200.2	206.3	208.7	205.9	202.5	199.1	197.9	195.9	
Bulls	000 head	49.5	49.3	49.5	47.2	44.8	42.3	40.1	38.0	35.8	33.5	31.1	
Dairy Heifers	000 head	335.7	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3	
Other Heifers	000 head	138.4	136.4	138.1	130.6	124.3	119.6	116.9	114.4	111.5	108.2	104.7	
Dairy Cows	kg CH4 hd-1	122.4	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5	
Other Cows	kg CH4 hd-1	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	
Cattle < 1 yrs - male	kg CH4 hd-1	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	29.7	
Cattle 1 - 2 yrs - male	kg CH4 hd-1	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	59.1	

Cattle > 2 yrs - male	kg CH4 hd-1	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.0	
Cattle < 1 yrs - female	kg CH4 hd-1	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	27.7	
Cattle 1 - 2 yrs - female	kg CH4 hd-1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	47.0	
Cattle > 2 yrs - female	kg CH4 hd-1	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	22.6	
Bulls	kg CH4 hd-1	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	81.5	
Dairy Heifers	kg CH4 hd-1	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	
Other Heifers	kg CH4 hd-1	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	53.7	
Dairy Cows	tCH4 yr-1	189,785	191,484	198,290	201,674	201,988	203,338	206,544	210,407	214,280	217,809	220,859	
Other Cows	tCH4 yr-1	67,246	67,106	65,479	62,175	58,860	56,063	53,914	51,996	50,083	48,235	46,349	
Cattle < 1 yrs - male	tCH4 yr-1	36,523	36,523	37,647	36,898	37,762	38,114	37,759	37,312	36,921	36,682	30,538	
Cattle 1 - 2 yrs - male	tCH4 yr-1	50,422	50,422	46,528	45,602	46,669	47,105	46,665	46,113	45,630	45,334	45,703	
Cattle > 2 yrs - male	tCH4 yr-1	13,684	13,684	14,053	13,773	14,096	14,227	14,095	13,928	13,782	13,693	13,396	
Cattle < 1 yrs - female	tCH4 yr-1	36,410	36,410	34,851	34,163	35,201	35,597	35,131	34,552	33,975	33,760	28,450	
Cattle 1 - 2 yrs - female	tCH4 yr-1	34,472	38,228	33,356	32,697	33,691	34,069	33,624	33,069	32,517	32,311	28,866	
Cattle > 2 yrs - female	tCH4 yr-1	5,214	4,745	4,292	4,207	4,335	4,384	4,326	4,255	4,184	4,157	4,418	
Bulls	tCH4 yr-1	4,622	4,604	4,627	4,412	4,179	3,949	3,744	3,545	3,342	3,129	2,536	
Dairy Heifers	tCH4 yr-1	18,437	16,298	16,843	16,746	16,754	16,934	17,171	17,406	17,604	17,754	17,863	
Other Heifers	tCH4 yr-1	8,089	7,975	8,074	7,631	7,268	6,994	6,832	6,686	6,517	6,325	5,621	

Total	tCH4 yr-1	464,905	467,479	464,039	459,977	460,802	460,774	459,804	459,269	458,833	459,188	444,599	
Dairy Cows	kg CH4 hd-1	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40	11.40	
Other Cows	kg CH4 hd-1	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	
Cattle < 1 yrs - male	kg CH4 hd-1	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	
Cattle 1 - 2 yrs - male	kg CH4 hd-1	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	
Cattle > 2 yrs - male	kg CH4 hd-1	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	
Cattle < 1 yrs - female	kg CH4 hd-1	4.66	4.66	4.66	4.66	4.66	4.66	4.66	4.66	4.66	4.66	4.66	
Cattle 1 - 2 yrs - female	kg CH4 hd-1	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	
Cattle > 2 yrs - female	kg CH4 hd-1	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	
Bulls	kg CH4 hd-1	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	
Dairy Heifers	kg CH4 hd-1	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	4.47	
Other Heifers	kg CH4 hd-1	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	
Dairy Cows	tCH4 yr-1	17,679	17,722	18,233	18,425	18,334	18,337	18,506	18,731	18,952	19,140	19,283	
Other Cows	tCH4 yr-1	6,975	6,961	6,792	6,449	6,105	5,815	5,592	5,393	5,195	5,003	4,807	
Cattle < 1 yrs - male	tCH4 yr-1	5,097	5,097	5,254	5,149	5,270	5,319	5,269	5,207	5,152	5,119	5,097	
Cattle 1 - 2 yrs - male	tCH4 yr-1	5,269	5,269	4,862	4,765	4,877	4,923	4,877	4,819	4,768	4,738	4,717	
Cattle > 2 yrs - male	tCH4 yr-1	541	541	555	544	557	562	557	550	545	541	539	

Cattle < 1 yrs - female	tCH4 yr-1	5,211	5,211	4,988	4,889	5,038	5,094	5,028	4,945	4,862	4,831	4,784	
Cattle 1 - 2 yrs - female	tCH4 yr-1	3,521	3,905	3,407	3,340	3,442	3,480	3,435	3,378	3,322	3,301	3,268	
Cattle > 2 yrs - female	tCH4 yr-1	60	54	49	48	50	50	50	49	48	48	47	
Bulls	tCH4 yr-1	500	498	500	477	452	427	405	383	361	338	314	
Dairy Heifers	tCH4 yr-1	1,501	1,327	1,371	1,364	1,364	1,379	1,398	1,417	1,433	1,446	1,455	
Other Heifers	tCH4 yr-1	708	698	706	668	636	612	598	585	570	553	535	
Total	**tCH4 yr-1**	**47,061.3**	**47,282.0**	**46,718.6**	**46,118.2**	**46,124.0**	**45,998.9**	**45,714.1**	**45,457.4**	**45,209.2**	**45,057.8**	**44,845.2**	
Increase in grazing time	percentage of yr	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**22%**	**Mean**
Reduction per day of grazing	Percentage	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	
Decrease in manure emissions	Percentage	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	
Proportion of population	Percentage	0.00%	0.00%	0.00%	1.00%	2.00%	3.00%	4.00%	6.00%	8.00%	9.00%	10.00%	
Reduction in Enteric methane	tCH4 yr-1	-	-	-	151.2	303.0	454.5	604.7	906.0	1,206.8	1,358.7	1,461.7	805.8
Reduction in manure methane	tCH4 yr-1				0.6	1.2	1.8	2.4	3.6	4.8	5.3	5.9	3.2
Total reduction	tCH4 yr-1				151.8	304.2	456.3	607.1	909.5	1,211.6	1,364.0	1,467.6	809.0
Total reduction	kt CO2e yr-1				4.3	8.5	12.8	17.0	25.5	33.9	38.2	41.1	22.7
Decrease in Milk footprint	Percentage d-1	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.00

Decrease in Beef Footprint	kg CO2e kg cwt-1 d-1	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.03
Dairy GHG	kt CO2e yr-1	8358	8516	8569	8617	8680	8875	9133	9232	9321	9381	9365	9,076
Dairy GHG	Billion litres	8.35	8.58	8.78	8.97	9.15	9.32	9.45	9.57	9.69	9.80	9.90	9.48
Milk footprint	kg CO2e l-1	1.001	0.992	0.975	0.960	0.949	0.952	0.966	0.964	0.962	0.957	0.946	0.96
Decrease in Milk footprint from increased grazing	Percentage	0.00%	0.00%	0.00%	0.14%	0.27%	0.41%	0.54%	0.82%	1.09%	1.22%	1.36%	0.01
Decrease in footprint emissions	kt CO2e yr-1	0.0	0.0	0.0	11.7	23.6	36.2	49.7	75.3	101.4	114.8	127.4	67.52
Beef prodn	t cwt yr-1	634000	595000	595651	595390	594544	593338	592061	590753	589322	587532	585675	591,077
Decrease in Beef footprint from increased grazing	kt CO2e yr-1	0.0	0.0	0.0	11.9	23.8	35.6	47.4	70.9	94.3	105.8	117.1	63.34
Total footprint impact	kt CO2e yr-1	0.0	0.0	0.0	23.6	47.4	71.8	97.0	146.2	195.7	220.6	244.5	130.86
Reduction in Milk cost of €3.24 per cow	€ yr-1	-	-	-	€52,377	€104,239	€156,386	€210,434	€319,479	€431,012	€489,691	€548,158	€288,972
Reduction in beef cost of €0.006 per kg per day	€ yr-1	0	0	0	€8,574	€17,123	€25,632	€34,103	€51,041	€67,890	€76,144	€84,337	€45,605
Total Cost Saving	€ yr-1	-	-	-	€60,950	€121,362	€182,018	€244,537	€370,520	€498,902	€565,835	€632,495	€334,577
Total abatement cost (footprint)	€ t-1 CO2e	0	0	0	-€2.58	-€2.56	-€2.53	-€2.52	-€2.53	-€2.55	-€2.57	-€2.59	-€3
Total abatement cost (absolute GHG)	€ t-1 CO2e	0	0	0	-14.34	-14.25	-14.25	-14.39	-14.55	-14.71	-14.82	-15.39	-14.59

Table A1.5: Overview of Modelling Assumptions Used and Results for Reduced Age of Finishing with Impacts of enhanced use of sexed semen

Pathway 1 (with 60% sexed semen)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Prime kill ('000)	1,263.9	1,270.8	1,268.0	1,271.6	1,254.6	1,240.1	1,231.9	1,225.6	1,219.3	1,212.4
Dairy cows	1,551.1	1,580.8	1,589.5	1,597.5	1,615.0	1,635.7	1,656.4	1,676.6	1,695.6	1,713.4
Numbers by group										
EM suckler heifers	36.8	35.9	34.5	33.9	32.5	31.4	30.3	29.3	28.3	27.2
LM suckler heifers	205.1	199.8	192.2	188.5	181.0	174.5	168.7	163.0	157.3	151.5
EM suckler steers	48.1	46.8	45.0	44.2	42.4	40.9	39.5	38.2	36.9	35.5
LM suckler steers	214.1	208.5	200.6	196.8	189.0	182.2	176.1	170.2	164.3	158.2
EM suckler bulls	7.0	6.8	6.5	6.4	6.1	5.9	5.7	5.5	5.3	5.1
LM suckler bulls	65.7	64.0	61.6	60.4	58.0	55.9	54.0	52.2	50.4	48.5
EM dairy heifers	167.9	179.8	190.5	199.5	205.1	210.5	217.5	225.0	232.6	240.0
LM dairy heifers	38.3	41.2	43.7	45.9	47.3	48.6	50.3	52.1	54.0	55.8
Dairy heifers	24.8	25.6	26.2	26.7	26.9	27.0	27.3	27.7	28.0	28.4
EM dairy steers	194.1	205.5	215.6	224.1	228.9	233.5	239.8	246.7	253.6	260.4
LM dairy steers	49.2	52.1	54.6	56.7	57.9	59.1	60.7	62.4	64.2	65.9
Dairy steers	160.0	151.4	142.8	134.1	125.5	116.8	108.2	99.5	90.9	82.2
LM dairy bulls	11.8	12.5	13.2	13.7	14.0	14.3	14.6	15.1	15.5	15.9
EM dairy bulls	6.7	8.2	9.6	10.9	11.8	12.8	13.8	15.0	16.1	17.2
Dairy bulls	34.4	32.8	31.3	29.8	28.2	26.7	25.2	23.6	22.1	20.6
Finishing age by group										
EM suckler heifers	24.4	24.2	23.9	23.7	23.5	23.2	23.0	22.7	22.5	22.3
LM suckler heifers	25.6	25.3	25.0	24.8	24.5	24.2	24.0	23.7	23.4	23.2
EM suckler steers	25.8	25.6	25.3	25.1	24.9	24.7	24.4	24.2	24.0	23.8
LM suckler steers	27.1	26.9	26.6	26.3	26.0	25.7	25.5	25.2	24.9	24.6
EM suckler bulls	18.4	18.1	17.9	17.7	17.5	17.2	17.0	16.8	16.5	16.3
LM suckler bulls	18.0	17.8	17.6	17.4	17.2	17.0	16.8	16.6	16.4	16.2
EM dairy heifers	24.1	23.8	23.5	23.2	22.9	22.7	22.4	22.1	21.8	21.5
LM dairy heifers	25.4	25.2	25.0	24.8	24.5	24.3	24.1	23.9	23.6	23.4
Dairy heifers	26.7	26.6	26.4	26.2	26.1	25.9	25.8	25.6	25.5	25.3
EM dairy steers	26.0	25.8	25.5	25.3	25.1	24.9	24.7	24.4	24.2	24.0

Pathway 1 (with 60% sexed semen)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LM dairy steers	26.9	26.7	26.5	26.3	26.1	25.9	25.6	25.4	25.2	25.0
Dairy steers	26.6	26.4	26.2	26.0	25.8	25.6	25.4	25.2	25.0	24.8
LM dairy bulls	20.4	20.0	19.7	19.4	19.1	18.7	18.4	18.1	17.8	17.4
EM dairy bulls	20.1	19.8	19.5	19.2	18.9	18.6	18.3	18.0	17.7	17.4
Dairy bulls	20.9	20.5	20.2	19.8	19.4	19.0	18.7	18.3	17.9	17.6
Average finishing age	25.2	25.0	24.7	24.5	24.2	24.0	23.7	23.4	23.2	22.9
Emissions savings per month finishing age reduction (kg/head)		168.7	168.7	168.7	168.7	168.7	168.7	168.7	168.7	168.7
Effect of earlier finishing on margin (€/d/head)										
Beef x Beef	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Beef x Dairy	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Dairy x Dairy	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
€ benefit by group (€,000)										
EM suckler heifers		196.9	189.5	185.9	178.5	172.1	166.3	160.7	155.1	149.4
LM suckler heifers		1225.4	1179.0	1156.6	1110.6	1070.7	1034.9	1000.1	965.1	929.5
EM suckler steers		241.5	232.4	228.0	218.9	211.0	204.0	197.1	190.2	183.2
LM suckler steers		1333.1	1282.6	1258.2	1208.2	1164.8	1125.9	1088.0	1049.9	1011.2
EM suckler bulls		36.4	35.0	34.3	33.0	31.8	30.7	29.7	28.7	27.6
LM suckler bulls		306.0	294.4	288.9	277.4	267.4	258.5	249.8	241.0	232.1
EM dairy heifers		1107.9	1173.5	1229.2	1263.4	1296.7	1339.8	1386.3	1432.8	1478.7
LM dairy heifers		199.1	211.5	222.1	228.7	235.1	243.4	252.3	261.2	269.9
Dairy heifers		85.5	87.7	89.4	89.9	90.4	91.4	92.5	93.7	94.8
EM dairy steers		966.6	1014.2	1053.9	1076.5	1098.3	1128.0	1160.4	1192.7	1224.6
LM dairy steers		236.9	248.4	258.1	263.6	268.9	276.1	284.0	291.8	299.6
Dairy steers		657.5	620.0	582.4	544.9	507.3	469.8	432.3	394.7	357.2
LM dairy bulls		87.2	91.5	95.2	97.2	99.2	102.0	104.9	107.9	110.8
EM dairy bulls		52.7	61.7	69.8	75.9	81.9	88.9	96.1	103.4	110.6
Dairy bulls		260.7	248.5	236.3	224.1	212.0	199.8	187.6	175.4	163.3

Pathway 1 (with 60% sexed semen)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Total € benefit (€,000)		6993.2	6969.9	6988.4	6890.7	6807.6	6759.3	6721.8	6683.7	6642.5
Abatement by group (kt CO2e)										
EM suckler heifers		1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.1	1.1
LM suckler heifers		8.9	8.6	8.4	8.1	7.8	7.6	7.3	7.0	6.8
EM suckler steers		1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.4	1.3
LM suckler steers		9.7	9.4	9.2	8.8	8.5	8.2	7.9	7.7	7.4
EM suckler bulls		0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
LM suckler bulls		2.2	2.1	2.1	2.0	2.0	1.9	1.8	1.8	1.7
EM dairy heifers		8.8	9.3	9.7	10.0	10.3	10.6	11.0	11.3	11.7
LM dairy heifers		1.6	1.7	1.8	1.8	1.9	1.9	2.0	2.1	2.1
Dairy heifers		0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8
EM dairy steers		7.7	8.0	8.3	8.5	8.7	8.9	9.2	9.4	9.7
LM dairy steers		1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.4
Dairy steers		5.2	4.9	4.6	4.3	4.0	3.7	3.4	3.1	2.8
LM dairy bulls		0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9
EM dairy bulls		0.4	0.5	0.6	0.6	0.6	0.7	0.8	0.8	0.9
Dairy bulls		2.1	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3
Pathway 1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		53.3	53.3	53.3	53.3	53.3	53.3	53.3	53.3	53.3
2023 abatement contribution			53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2
2024 abatement contribution				53.4	53.4	53.4	53.4	53.4	53.4	53.4
2025 abatement contribution					52.7	52.7	52.7	52.7	52.7	52.7
2026 abatement contribution						52.1	52.1	52.1	52.1	52.1
2027 abatement contribution							51.8	51.8	51.8	51.8
2028 abatement contribution								51.5	51.5	51.5
2029 abatement contribution									51.3	51.3
2030 abatement contribution										51.0
Total annual abatement		**53.3**	**106.5**	**159.9**	**212.6**	**264.7**	**316.5**	**368.0**	**419.3**	**470.4**
Cumulative		53.3	159.8	319.7	532.3	797.0	1113.5	1481.5	1900.8	2371.2
MAC (€/kt)		-131.2	-131.0	-130.9	-130.8	-130.7	-130.5	-130.4	-130.3	-130.2

Pathway 1 (with 60% sexed semen)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total CO2e 2021-2025 (kt)	**532.3**									
Total CO2e 2021-2030 (kt)	**2371.2**									

Pathway 2 (with 90% sexed semen)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Prime kill ('000)	1,263.9	1,270.8	1,268.0	1,271.6	1,254.6	1,240.1	1,231.9	1,225.6	1,219.3	1,212.4
Dairy cows	1,551.1	1,580.8	1,589.5	1,597.5	1,615.0	1,635.7	1,656.4	1,676.6	1,695.6	1,713.4
Numbers by group										
EM suckler heifers	36.8	35.9	34.5	33.9	32.5	31.4	30.3	29.3	28.3	27.2
LM suckler heifers	205.1	199.8	192.2	188.5	181.0	174.5	168.7	163.0	157.3	151.5
EM suckler steers	48.1	46.8	45.0	44.2	42.4	40.9	39.5	38.2	36.9	35.5
LM suckler steers	214.1	208.5	200.6	196.8	189.0	182.2	176.1	170.2	164.3	158.2
EM suckler bulls	7.0	6.8	6.5	6.4	6.1	5.9	5.7	5.5	5.3	5.1
LM suckler bulls	65.7	64.0	61.6	60.4	58.0	55.9	54.0	52.2	50.4	48.5
EM dairy heifers	167.9	183.2	197.3	209.8	218.8	227.6	238.0	249.0	260.0	270.8
LM dairy heifers	38.3	42.0	45.4	48.5	50.7	52.9	55.4	58.1	60.8	63.5
Dairy heifers	24.8	25.6	26.2	26.7	26.9	27.0	27.3	27.7	28.0	28.4
EM dairy steers	194.1	208.2	221.1	232.3	239.8	247.2	256.3	265.9	275.5	285.0
LM dairy steers	49.2	52.7	56.0	58.8	60.7	62.5	64.8	67.2	69.6	72.0
Dairy steers	160.0	144.5	129.0	113.5	98.0	82.6	67.1	51.6	36.1	20.6
LM dairy bulls	11.8	12.7	13.5	14.2	14.7	15.1	15.7	16.3	16.9	17.5
EM dairy bulls	6.7	8.9	11.0	12.9	14.6	16.2	17.9	19.8	21.6	23.4
Dairy bulls	34.4	31.1	27.9	24.6	21.4	18.1	14.9	11.6	8.4	5.1
Finishing age by group										
EM suckler heifers	24.4	24.1	23.7	23.4	23.1	22.8	22.4	22.1	21.8	21.4
LM suckler heifers	25.6	25.2	24.9	24.5	24.2	23.9	23.5	23.2	22.9	22.5
EM suckler steers	25.8	25.5	25.2	25.0	24.7	24.5	24.2	23.9	23.7	23.4
LM suckler steers	27.1	26.8	26.5	26.2	25.8	25.5	25.2	24.9	24.6	24.2
EM suckler bulls	18.4	18.1	17.8	17.5	17.2	16.9	16.7	16.4	16.1	15.8
LM suckler bulls	18.0	17.8	17.5	17.3	17.0	16.7	16.5	16.2	16.0	15.7
EM dairy heifers	24.1	23.6	23.0	22.4	21.9	21.3	20.8	20.2	19.7	19.1

Pathway 2 (with 90% sexed semen)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LM dairy heifers	25.4	25.0	24.5	24.0	23.5	23.0	22.5	22.0	21.5	21.0
Dairy heifers	26.7	26.5	26.3	26.1	25.9	25.7	25.5	25.3	25.1	24.9
EM dairy steers	26.0	25.6	25.3	24.9	24.6	24.2	23.9	23.6	23.2	22.9
LM dairy steers	26.9	26.6	26.3	26.0	25.7	25.4	25.0	24.7	24.4	24.1
Dairy steers	26.6	26.4	26.1	25.8	25.5	25.3	25.0	24.7	24.4	24.1
LM dairy bulls	20.4	20.0	19.5	19.1	18.7	18.3	17.9	17.5	17.1	16.7
EM dairy bulls	20.1	19.7	19.3	18.9	18.6	18.2	17.8	17.4	17.1	16.7
Dairy bulls	20.9	20.5	20.0	19.6	19.1	18.6	18.2	17.7	17.3	16.8
Average finishing age	25.2	24.9	24.5	24.1	23.7	23.3	22.9	22.5	22.1	21.6
Emissions savings per month finishing age reduction (kg/head)		175.9	175.9	175.9	175.9	175.9	175.9	175.9	175.9	175.9
Effect of earlier finishing on margin (€/d/head)										
Beef x Beef	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Beef x Dairy	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Dairy x Dairy	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
€ benefit by group (€,000)										
EM suckler heifers		274.9	264.5	259.4	249.1	240.2	232.1	224.3	216.5	208.5
LM suckler heifers		1556.1	1497.2	1468.8	1410.4	1359.7	1314.3	1270.1	1225.7	1180.4
EM suckler steers		285.2	274.4	269.1	258.4	249.2	240.8	232.7	224.6	216.3
LM suckler steers		1541.6	1483.2	1455.1	1397.2	1347.0	1302.0	1258.2	1214.2	1169.4
EM suckler bulls		45.0	43.3	42.5	40.8	39.3	38.0	36.7	35.4	34.1
LM suckler bulls		377.5	363.2	356.3	342.2	329.9	318.9	308.1	297.4	286.4
EM dairy heifers		2157.9	2323.8	2470.6	2576.2	2680.2	2803.1	2932.3	3061.5	3189.5
LM dairy heifers		443.6	479.7	511.9	535.3	558.4	585.5	613.9	642.3	670.5
Dairy heifers		107.3	110.0	112.2	112.8	113.3	114.6	116.1	117.5	118.9
EM dairy steers		1543.1	1638.5	1721.4	1777.2	1831.9	1899.1	1970.4	2041.6	2112.2
LM dairy steers		351.7	373.3	392.1	404.6	417.0	432.1	448.2	464.3	480.3
Dairy steers		858.0	766.0	674.0	582.0	490.0	398.1	306.1	214.1	122.1
LM dairy bulls		110.8	117.7	123.7	127.8	131.8	136.8	142.0	147.2	152.3

Pathway 2 (with 90% sexed semen)	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
EM dairy bulls		71.8	88.7	104.5	117.7	130.8	145.1	159.7	174.4	189.0
Dairy bulls		299.5	268.3	237.0	205.8	174.5	143.2	112.0	80.7	49.5
Total € benefit (€,000)		10024.1	10091.9	10198.7	10137.7	10093.3	10103.5	10130.9	10157.4	10179.4
Abatement by group (kt CO2e)										
EM suckler heifers		2.1	2.0	2.0	1.9	1.8	1.8	1.7	1.6	1.6
LM suckler heifers		11.8	11.4	11.2	10.7	10.3	10.0	9.7	9.3	9.0
EM suckler steers		2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.7	1.6
LM suckler steers		11.7	11.3	11.1	10.6	10.3	9.9	9.6	9.2	8.9
EM suckler bulls		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
LM suckler bulls		2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.3	2.2
EM dairy heifers		17.8	19.2	20.4	21.3	22.1	23.2	24.2	25.3	26.4
LM dairy heifers		3.7	4.0	4.2	4.4	4.6	4.8	5.1	5.3	5.5
Dairy heifers		0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0
EM dairy steers		12.7	13.5	14.2	14.7	15.1	15.7	16.3	16.9	17.5
LM dairy steers		2.9	3.1	3.2	3.3	3.4	3.6	3.7	3.8	4.0
Dairy steers		7.1	6.3	5.6	4.8	4.0	3.3	2.5	1.8	1.0
LM dairy bulls		0.9	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.3
EM dairy bulls		0.6	0.7	0.9	1.0	1.1	1.2	1.3	1.4	1.6
Dairy bulls		2.5	2.2	2.0	1.7	1.4	1.2	0.9	0.7	0.4
Moderate	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
2022 abatement contribution		80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2	80.2
2023 abatement contribution			80.8	80.8	80.8	80.8	80.8	80.8	80.8	80.8
2024 abatement contribution				81.8	81.8	81.8	81.8	81.8	81.8	81.8
2025 abatement contribution					81.3	81.3	81.3	81.3	81.3	81.3
2026 abatement contribution						81.1	81.1	81.1	81.1	81.1
2027 abatement contribution							81.2	81.2	81.2	81.2
2028 abatement contribution								81.5	81.5	81.5
2029 abatement contribution									81.8	81.8
2030 abatement contribution										82.1
Total annual abatement ($ktCO_2e\ yr^{-1}$)		**80.2**	**161.0**	**242.7**	**324.1**	**405.1**	**486.4**	**567.9**	**649.7**	**731.8**

Pathway 2 (with 90% sexed semen)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cumulative		80.2	241.1	483.9	808.0	1213.1	1699.5	2267.4	2917.1	3649.0
MAC (€/kt)		**-125.1**	**-124.9**	**-124.8**	**-124.6**	**-124.5**	**-124.4**	**-124.3**	**-124.1**	**-124.0**
Total CO2e 2021-2025 (kt)	**808.0**									
Total CO2e 2021-2030 (kt)	**3649.0**									

Table A1.6: Overview of Modelling Assumptions Used and Results for Liming/pH manipulation

Scenario A												
Uptake linear												
Lime	Unit											
Emissions avoided due to liming		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Lime spread (BAU)	t lime yr^{-1}	898650	896040	878158	902540	894479	893973	893038	892438	895294	893845	893718	893352
Extra lime	t lime yr^{-1}	0	720039	981133	944227	996963	1085301	1148479	1205395	1194526	1211627	1156155	1200000
Total Lime spread	t lime yr^{-1}	898650	1616079	1859291	1846767	1891443	1979275	2041517	2097833	2089820	2105472	2049873	1957737
extra hectares impacted pa	ha yr^{-1}	0	144008	196227	188845	199393	217060	229696	241079	238905	242325	231231	212877
Cumulative extra ha impacted	ha yr^{-1}	0	144008	332853	532246	749306	834994	887228	926740	952006	953541	952462	726538
N saving (t N pa)	t N yr^{-1}	0	8640	19971	31935	44958	50100	53234	55604	57120	57212	57148	43592
N_2O Reduction	t N_2O-N yr^{-1}	0	121.0	279.6	447.1	629.4	701.4	745.3	778.5	799.7	801.0	800.1	610
Reduction in CO_2 equivalents	kt CO_2e yr^{-1}	0	50	116	186	262	292	310	324	333	334	333	254.14
Reduction in N_2O emission factor due to pH change		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Mineral N applied assuming the 50% of the land is fertilised @110 kg N ha	t N yr^{-1}	0	7920	18307	29274	41212	45925	48798	50971	52360	52445	52385	39960
Grassland N_2O EF	kg N_2O-N kg^{-1} N	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	0

Associated N_2O emissions	t N_2O-N yr^{-1}	0	110.9	256.3	409.8	577.0	642.9	683.2	713.6	733.0	734.2	733.4	559
Reduction in N2O associated with pH change of 1 unit	t N_2O-N yr^{-1}	0	43.2	100.0	159.8	225.0	250.7	266.4	278.3	285.9	286.3	286.0	218
Reduction in CO2 equivalents	kt CO_2e yr^{-1}	0	18.0	41.6	66.6	93.7	104.4	111.0	115.9	119.1	119.2	119.1	91
Extra SOC sequestration	kt CO_2e yr^{-1}	0	72	166	266	375	417	444	463	476	477	476	363
Total N2O mitigation	kt CO_2e yr^{-1}	0	68.4	158.1	252.7	355.8	396.5	421.3	440.1	452.1	452.8	452.3	345
CO_2 emissions from liming (Tier 1)	kt CO_2e yr^{-1}	0	316.8	431.7	415.5	438.7	477.5	505.3	530.4	525.6	533.1	508.7	468.33
CO_2 emissions from liming (Tier 2)	kt CO_2e yr^{-1}	0	158.4	215.8	207.7	219.3	238.8	252.7	265.2	262.8	266.6	254.4	234.16
Net mitigation (non-CO_2) - Tier 1	kt CO_2e yr^{-1}	**0**	**-85.9**	**-52.2**	**50.4**	**142.1**	**163.9**	**175.2**	**181.7**	**196.0**	**193.1**	**204.5**	**116.87**
Net mitigation (CO_2) - Tier 1	kt CO_2e yr^{-1}	*0*	**-90.5**	**-55.0**	**53.0**	**149.7**	**172.6**	**184.4**	**191.3**	**206.4**	**203.3**	**215.3**	123.06
Net mitigation (non-CO2) - Tier 2	kt CO_2e yr^{-1}	**0**	**-8.8**	**52.9**	**151.6**	**249.0**	**280.2**	**298.2**	**310.9**	**324.1**	**323.0**	**328.4**	**230.94**
Net mitigation (CO2) - Tier 2	kt CO_2e yr^{-1}	0	**-9.2**	**55.7**	**159.6**	**262.2**	**295.0**	**314.0**	**327.4**	**341.2**	**340.1**	**345.8**	**243.17**
Cost	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Price of lime & labour	€27 per tonne (17+10)	0	€19,441,056	€26,490,592	€25,494,121	€26,918,007	€29,303,136	€31,008,941	€32,545,666	€32,252,215	€32,713,940	€31,216,197	**€28,738,387**

Fuel	0.53 €/l	0	€228,972	€312,000	€300,264	€317,034	€345,126	€365,216	€383,316	€379,859	€385,298	€367,657	**€338,474**
Fertiliser N saving	1.2per kg N	0	€10,368,563	€23,965,428	€38,321,698	€53,950,037	€60,119,576	€63,880,400	€66,725,311	€68,544,407	€68,654,944	€68,577,255	**€52,310,762**
Fertiliser P saving	2.62 per kg P	0	€9,998,463	€13,624,013	€13,111,532	€13,843,831	€15,070,494	€15,947,783	€16,738,116	€16,587,195	€16,824,658	€16,054,375	**€14,780,046**
Total Cost	€ per year	0	-€696,998	€1,236,528	-€805,104	-€4,620,000	-€8,552,426	- €12,346,363	- €16,001,811	- €19,518,770	- €23,035,729	-€25,847,508	**- €11,018,818**
Euro per tCO2e			€8.11	-€23.68	-€15.98	-€32.50	-€52.18	-€70.49	-€88.06	-€99.56	-€119.29	-€126.40	**-€62**
Cost	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Price of lime & labour	€32 per tonne (21+11)	0	€3,840,000	€7,680,000	€11,520,000	€15,360,000	€18,900,102	€22,440,205	€25,980,307	€29,520,410	€33,060,512	€38,400,000	**€20,670,154**
Fuel	1.3 €/l	0	€93,600	€187,200	€280,800	€374,400	€460,690	€546,980	€633,270	€719,560	€805,850	€936,000	**€503,835**
Fertiliser N saving	2.6 per kg N	0	€3,120,000	€9,360,000	€18,720,000	€31,200,000	€43,436,333	€55,429,000	€67,177,999	€78,683,332	€90,188,665	€103,155,998	**€50,047,133**
Fertiliser P saving	3.87 per kg P	0	€492,264	€1,476,792	€2,953,584	€4,922,640	€6,853,251	€8,745,417	€10,599,138	€12,414,414	€14,229,690	€16,275,636	**€7,896,283**
Total Cost	€ per year	0	€321,336	-€2,969,592	-€9,872,784	- €20,388,240	- €30,928,792	- €41,187,232	- €51,163,560	- €60,857,776	- €70,551,993	-€80,095,634	**- €36,769,427**
Euro per tCO2e			-€3.74	€56.86	-€196.02	-€143.44	-€188.71	-€235.15	-€281.55	-€310.43	-€365.35	-€391.69	**-€206**

Pathway 1	Uptake linear												
Lime	Unit												
Emissions avoided due to liming		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Lime spread (BAU)	t lime yr^{-1}	898650	896040	878158	902540	894479	893973	893038	892438	895294	893845	893718	893352
Extra lime	t lime yr^{-1}	0	110628	221256	331885	442513	553141	663769	774397	885026	995654	1106282	608455
Total Lime spread	t lime yr^{-1}	898650	1006668	1099414	1234425	1336992	1447114	1556807	1666835	1780319	1889498	2000000	1501807
extra hectares impacted pa	ha yr^{-1}	0	22126	44251	66377	88503	110628	132754	154879	177005	199131	221256	121691
Cumulative extra ha impacted	ha yr^{-1}	0	22126	66377	132754	221256	309759	398262	486764	575267	663769	752272	362860
N saving (t N pa)	t N yr^{-1}	0	1261	3783	7567	12612	17656	22701	27746	32790	37835	42879	20683
N_2O Reduction	t N_2O-N yr^{-1}	0	17.7	53.0	105.9	176.6	247.2	317.8	388.4	459.1	529.7	600.3	290

Reduction in CO_2 equivalents	kt CO_2e yr^{-1}	0	7	22	44	74	103	132	162	191	221	250	121
Reduction in N_2O emission factor due to pH change		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Mineral N applied assuming the 50% of the land is fertilised @110 kg N ha	t N yr^{-1}	0	1217	3651	7301	12169	17037	21904	26772	31640	36507	41375	19957
Grassland N_2O EF	kg N_2O-N kg^{-1} N	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	0
Associated N_2O emissions	t N_2O-N yr^{-1}	0	17.0	51.1	102.2	170.4	238.5	306.7	374.8	443.0	511.1	579.2	279
Reduction in N2O associated with pH change of 1 unit	t N_2O-N yr^{-1}	0	6.6	19.9	39.9	66.4	93.0	119.6	146.2	172.8	199.3	225.9	109
Reduction in CO2 equivalents	kt CO_2e yr^{-1}	0	2.8	8.3	16.6	27.7	38.7	49.8	60.9	71.9	83.0	94.1	45
Extra SOC sequestration	kt CO_2e yr^{-1}	0	11	33	66	111	155	199	243	288	332	376	181
Total N2O mitigation	kt CO_2e yr^{-1}	0	10.1	30.4	60.7	101.2	141.7	182.2	222.6	263.1	303.6	344.1	166
CO_2 emissions from liming (Tier 1)	kt CO_2e yr^{-1}	0	48.7	97.4	146.0	194.7	243.4	292.1	340.7	389.4	438.1	486.8	267.72
CO_2 emissions from liming (Tier 2)	kt CO_2e yr^{-1}	0	24.3	48.7	73.0	97.4	121.7	146.0	170.4	194.7	219.0	243.4	133.86
Net mitigation (non-CO_2) - Tier 1	kt CO_2e yr^{-1}	**0**	**-13.1**	**-16.2**	**-9.0**	**8.2**	**25.4**	**42.6**	**59.8**	**77.1**	**94.3**	**111.5**	**38.06**
Net mitigation (CO_2) - Tier 1	kt CO_2e yr^{-1}	0	**-14.4**	**-17.7**	**-9.9**	**8.9**	**27.8**	**46.6**	**65.4**	**84.3**	**103.1**	**121.9**	**41.61**
Net mitigation (non-CO2) - Tier 2	kt CO_2e yr^{-1}	**0**	**-1.5**	**7.1**	**25.8**	**54.7**	**83.5**	**112.4**	**141.2**	**170.1**	**198.9**	**227.8**	**102.01**
Net mitigation (CO2) - Tier 2	kt CO_2e yr^{-1}	0	**-1.6**	**7.8**	**28.2**	**59.8**	**91.3**	**122.9**	**154.4**	**185.9**	**217.5**	**249.0**	**111.52**
Low Cost	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Price of lime & labour	€27 per tonne (17+10)	0	€2,986,961	€5,973,923	€8,960,884	€11,947,846	€14,934,807	€17,921,768	€20,908,730	€23,895,691	€26,882,653	€29,869,614	**€16,428,288**
Fuel	0.53 €/l	0	€35,180	€70,360	€105,539	€140,719	€175,899	€211,079	€246,258	€281,438	€316,618	€351,798	**€193,489**
Fertiliser N saving	1.2per kg N	0	€1,513,394	€4,540,181	€9,080,363	€15,133,938	€21,187,513	€27,241,088	€33,294,663	€39,348,238	€45,401,813	€51,455,388	**€24,819,658**

Fertiliser P saving	2.62 per kg P	0	€1,536,183	€3,072,366	€4,608,550	€6,144,733	€7,680,916	€9,217,099	€10,753,282	€12,289,465	€13,825,649	€15,361,832	**€8,449,008**
Total Cost N2O	€ per year	0	-€13,992	-€799,815	-€2,357,469	-€4,686,954	-€7,016,439	-€9,345,923	-€11,675,408	-€14,004,893	-€16,334,378	-€18,663,862	**-€8,489,913**
Abatement cost N2O	€ $t^{-1}CO_2e$		€1.07	€49.52	€260.61	-€573.16	-€573.16	-€219.26	-€195.08	-€181.71	-€173.23	-€167.36	**-€177**
Total Cost CO2	€ per year		-€13,444	-€768,450	-€2,265,019	-€4,503,152	-€6,741,284	-€8,979,417	-€11,217,549	-€13,455,681	-€15,693,814	-€17,931,946	**-€8,156,976**
Abatement cost CO2	€ $t^{-1}CO_2e$		*€0.94*	*€43.52*	*€229.03*	*-€503.72*	*-€242.76*	*-€192.70*	*-€171.45*	*-€159.70*	*-€152.24*	*-€147.09*	**-€130**
High Cost	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Price of lime & labour	€32 per tonne (21+11)	0	€3,840,000	€7,680,000	€11,520,000	€15,360,000	€18,900,102	€22,440,205	€25,980,307	€29,520,410	€33,060,512	€38,400,000	**€20,670,154**
Fuel	1.3 €/l	0	€93,600	€187,200	€280,800	€374,400	€460,690	€546,980	€633,270	€719,560	€805,850	€936,000	**€503,835**
Fertiliser N saving	2.6 per kg N	0	€3,120,000	€9,360,000	€18,720,000	€31,200,000	€43,436,333	€55,429,000	€67,177,999	€78,683,332	€90,188,665	€103,155,998	**€50,047,133**
Fertiliser P saving	3.87 per kg P	0	€492,264	€1,476,792	€2,953,584	€4,922,640	€6,853,251	€8,745,417	€10,599,138	€12,414,414	€14,229,690	€16,275,636	**€7,896,283**
Total Cost N2O	€ per year	€0	€163,881	-€1,514,492	-€5,035,120	-€10,398,002	-€15,773,684	-€21,005,488	-€26,093,416	-€31,037,466	-€35,981,516	-€40,848,774	-€18,752,408
Abatement cost N2O	€ $t^{-1}CO_2e$		-€12.48	€93.78	€556.61	-€1,271.55	-€620.99	-€492.80	-€435.99	-€402.71	-€381.58	-€366.30	-€333
Total Cost CO2	€ per year		€157,455	-€1,455,100	-€4,837,664	-€9,990,238	-€15,155,108	-€20,181,744	-€25,070,144	-€29,820,310	-€34,570,476	-€39,246,861	-€18,017,019
Abatement cost CO2	€ $t^{-1}CO_2e$		*-€10.97*	*€82.41*	*€489.18*	*-€1,117.51*	*-€545.76*	*-€433.10*	*-€383.18*	*-€353.92*	*-€335.36*	*-€321.92*	-€293

Pathway 2	Uptake - Linear											
Lime	Unit											
Emissions avoided due to liming		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Lime spread (BAU)	t lime yr^{-1}	898650	896040	878158	902540	894479	893973	893038	892438	895294	893845	893718	893352
Extra lime	t lime yr^{-1}	0	160628	321256	481885	642513	803141	963769	1124397	1285026	1445654	1606282	883455

Total Lime spread	t lime yr^{-1}	898650	1056668	1199414	1384425	1536992	1697114	1856807	2016835	2180319	2339498	2500000	1776807
extra hectares impacted pa	ha yr^{-1}	0	32126	64251	96377	128503	160628	192754	224879	257005	289131	321256	176691
Cumulative extra ha impacted	ha yr^{-1}	0	32126	96377	192754	321256	449759	578262	706764	835267	963769	1092272	526860
N saving (t N pa)	t N yr^{-1}	0	1831	5493	10987	18312	25636	32961	40286	47610	54935	62259	30031
N_2O Reduction	t N_2O-N yr^{-1}	0	25.6	76.9	153.8	256.4	358.9	461.5	564.0	666.5	769.1	871.6	420
Reduction in CO_2 equivalents	kt CO_2e yr^{-1}	0	11	32	64	107	149	192	235	278	320	363	169.03
Reduction in N_2O emission factor due to pH change		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Mineral N applied assuming the 50% of the land is fertilised @110 kg N ha	t N yr^{-1}	0	1767	5301	10601	17669	24737	31804	38872	45940	53007	60075	28977
Grassland N_2O EF	kg N_2O-N kg^{-1} N	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	0
Associated N_2O emissions	t N_2O-N yr^{-1}	0	24.7	74.2	148.4	247.4	346.3	445.3	544.2	643.2	742.1	841.0	406
Reduction in N2O associated with pH change of 1 unit	t N_2O-N yr^{-1}	0	9.6	28.9	57.9	96.5	135.1	173.7	212.2	250.8	289.4	328.0	158.2
Reduction in CO2 equivalents	kt CO_2e yr^{-1}	0	4.0	12.1	24.1	40.2	56.2	72.3	88.4	104.5	120.5	136.6	65.9
Extra SOC sequestration	kt CO_2e yr^{-1}	0	16	48	96	161	225	289	353	418	482	546	263.4
Total N2O mitigation	kt CO_2e yr^{-1}	0	14.7	44.1	88.2	146.9	205.7	264.5	323.2	382.0	440.8	499.6	241.0
CO_2 emissions from liming (Tier 1)	kt CO_2e yr^{-1}	0	70.7	141.4	212.0	282.7	353.4	424.1	494.7	565.4	636.1	706.8	388.7
CO_2 emissions from liming (Tier 2)	kt CO_2e yr^{-1}	0	35.3	70.7	106.0	141.4	176.7	212.0	247.4	282.7	318.0	353.4	194.4
Net mitigation (non-CO_2) - Tier 1	**kt CO_2e yr^{-1}**	**0**	**-19.1**	**-23.4**	**-13.1**	**11.9**	**36.9**	**61.9**	**86.9**	**111.9**	**136.9**	**161.9**	**55.3**
Net mitigation (CO_2) - Tier 1	kt CO_2e yr^{-1}	*0*	**-20.8**	**-25.6**	**-14.4**	**13.0**	**40.3**	**67.7**	**95.0**	**122.3**	**149.7**	**177.0**	**60.4**
Net mitigation (non-CO2) - Tier 2	**kt CO_2e yr^{-1}**	**0**	**-2.2**	**10.3**	**37.5**	**79.4**	**121.3**	**163.2**	**205.1**	**247.0**	**288.9**	**330.7**	**148.1**
Net mitigation (CO2) - Tier 2	kt CO_2e yr^{-1}	0	**-2.4**	**11.3**	**41.0**	**86.8**	**132.6**	**178.4**	**224.2**	**270.0**	**315.8**	**361.6**	**161.9**

Cost (Low)	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030.00**	**Mean**
Price of lime & labour	€27 per tonne (17+10)	0	€4,336,961	€8,673,923	€13,010,884	€17,347,846	€21,684,807	€26,021,768	€30,358,730	€34,695,691	€39,032,653	€43,369,614	€23,853,288
Fuel	.53 €/l	0	€51,080	€102,160	€153,239	€204,319	€255,399	€306,479	€357,558	€408,638	€459,718	€510,798	€280,939
Fertiliser N saving	1.2per kg N	0	€2,197,394	€6,592,181	€13,184,363	€21,973,938	€30,763,513	€39,553,088	€48,342,663	€57,132,238	€65,921,813	€74,711,388	€36,037,258
Fertiliser P saving	2.62 per kg P	0	€2,230,483	€4,460,966	€6,691,450	€8,921,933	€11,152,416	€13,382,899	€15,613,382	€17,843,865	€20,074,349	€22,304,832	€12,267,658
Total Cost N2O	€ per year	0	-€20,316	-€1,161,303	-€3,422,961	-€6,805,290	-€10,187,619	-€13,569,947	-€16,952,276	-€20,334,605	-€23,716,934	-€27,099,262	-€12,327,051
Abatement cost N2O	€ $t^{-1}CO_2e$		€1.07	€49.52	€260.61	-€573.16	-€573.16	-€219.26	-€195.08	-€181.71	-€173.23	-€167.36	-€177
Total Cost CO2	€ per year		-€19,520	-€1,115,762	-€3,288,727	-€6,538,416	-€9,788,104	-€13,037,793	-€16,287,481	-€19,537,169	-€22,786,858	-€26,036,546	-€11,843,638
Abatement cost CO2	€ $t^{-1}CO_2e$		*€0.94*	*€43.52*	*€229.03*	*-€503.72*	*-€242.76*	*-€192.70*	*-€171.45*	*-€159.70*	*-€152.24*	*-€147.09*	-€130
Cost (high)	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Price of lime & labour	€32 per tonne (21+11)	€0	€5,140,102	€6,103,190	€13,769,801	€25,600,000	€37,430,199	€45,096,810	€48,771,795	€50,279,106	€50,857,326	€51,200,000	€33,424,833
Fuel	1.3 €/l	€0	€125,290	€148,765	€335,639	€624,000	€912,361	€1,099,235	€1,188,813	€1,225,553	€1,239,647	€1,248,000	€814,730
Fertiliser N saving	2.6 per kg N	€0	€4,761,020	€14,283,060	€28,566,119	€47,610,198	€66,654,278	€85,698,357	€104,742,437	€123,786,516	€142,830,595	€161,874,675	€78,080,726
Fertiliser P saving	3.87 per kg P	€0	€3,294,645	€6,589,290	€9,883,935	€13,178,580	€16,473,225	€19,767,870	€23,062,515	€26,357,160	€29,651,805	€32,946,450	€18,120,548
Total Cost N2O	€ per year	€0	-€1,423,039	-€7,456,401	-€12,415,753	-€17,628,037	-€22,840,321	-€30,227,793	-€39,700,615	-€50,305,899	-€61,396,568	-€72,610,294	-€31,600,472
Abatement cost N2O	€ $t^{-1}CO_2e$		€74.62	€317.98	€945.27	-€1,484.68	-€619.29	-€488.42	-€456.87	-€449.54	-€448.43	-€448.43	-€306
Total Cost CO2	€ per year		-€1,367,234	-€7,163,993	-€11,928,861	-€16,936,741	-€21,944,622	-€29,042,389	-€38,143,729	-€48,333,118	-€58,988,859	-€69,762,831	-€30,361,238
Abatement cost CO2	€ $t^{-1}CO_2e$		*€65.58*	*€279.46*	*€830.75*	*-€1,304.81*	*-€544.27*	*-€429.25*	*-€401.52*	*-€395.08*	*-€394.11*	*-€394.10*	-€269

Table A1.7: Overview of Modelling Assumptions Used and Results for Inclusion of clover & Multi-species swards

Pathway 1		Ha	No farms	total ha		reseed rate	ha reseeded p.a.	Uptake					
Average UAA Dairy		61	18000	1098000	reseed pa	0.06	65880	0.65	80KgN replacement				
Average UAA Non-dairy		32	80000	2560000	reseed pa	0.01	25600	0.3	30 kgN replacement				
		2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Dairy Farms	No. farms	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	
Non-dairy bovine Farms	No. farms	80000	80000	80000	80000	80000	80000	80000	80000	80000	80000	80000	
Average dairy UAA	ha	61	61	61	61	61	61	61	61	61	61	61	
Average non-dairy UAA	ha	32	32	32	32	32	32	32	32	32	32	32	
Reseed rate dairy	percentage	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	
Reseed rate non-dairy	percentage	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	
Uptake dairy	percentage	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	
Uptake non-dairy	percentage	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
N replacement by clover dairy	kg N yr^{-1}	80	80	80	80	80	80	80	80	80	80	80	
N replacement by clover non-dairy	kg N yr^{-1}	20	20	20	20	20	20	20	20	20	20	20	
Hectares reseeded dairy	ha	0	39528	79056	118584	158112	197640	237168	276696	316224	355752	395280	197640.0
Hectares reseeded non-dairy	ha	0	7680	15360	23040	30720	38400	46080	53760	61440	69120	76800	38400.0
Dairy N replaced	t N yr^{-1}	0	3162	6324	9487	12649	15811	18973	22136	25298	28460	31622	15811.2
Non-Dairy N replaced	t N yr^{-1}	0	154	307	461	614	768	922	1075	1229	1382	1536	768.0
Total N replaced	t N yr^{-1}	0	3316	6632	9948	13263	16579	19895	23211	26527	29843	33158	16579.2
N2O avoided (tN yr)	t N_2O-N yr^{-1}	0	46.4	92.8	139.3	185.7	232.1	278.5	325.0	371.4	417.8	464.2	232.1
Abatement in CO2 equivalents	kt CO_2e yr^{-1}	0	19.3	38.7	58.0	77.3	96.7	116.0	135.3	154.7	174.0	193.3	96.7

Extra SOC -mean from DAYCENT	t CO_2e yr^{-1}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SOC	kt CO_2e yr^{-1}	0	23.60	47.21	70.81	94.42	118.02	141.62	165.23	188.83	212.44	236.04	118.0
Pathway 2	Ha	No farms	total ha		reseed rate	ha reseeded p.a.	Uptake						
Average UAA Dairy	61	18000	1,098,000	reseed pa	8%	87840	80.00%	70KgN replacement					
Average UAA Non-dairy	32	80000	2,560,000	reseed pa	2%	51200	50.00%	30 kgN replacement					
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Dairy Farms	No. farms	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	18000	
Non-dairy bovine Farms	No. farms	80000	80000	80000	80000	80000	80000	80000	80000	80000	80000	80000	
Average dairy UAA	ha	61	61	61	61	61	61	61	61	61	61	61	
Average non-dairy UAA	ha	32	32	32	32	32	32	32	32	32	32	32	
Reseed rate dairy	percentage	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	
Reseed rate non-dairy	percentage	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	
Uptake dairy	percentage	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	
Uptake non-dairy	percentage	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
N replacement by clover dairy	kg N yr^{-1}	80	80	80	80	80	80	80	80	80	80	80	
N replacement by clover non-dairy	kg N yr^{-1}	30	30	30	30	30	30	30	30	30	30	30	
Hectares reseeded dairy	ha	0	52704	105408	158112	210816	263520	316224	368928	421632	474336	527040	263520.0
Hectares reseeded non-dairy	ha	0	23040	46080	69120	92160	115200	138240	161280	184320	207360	230400	115200.0
Dairy N replaced	t N yr^{-1}	0	4216	8433	12649	16865	21082	25298	29514	33731	37947	42163	21081.6
Non-Dairy N replaced	t N yr^{-1}	0	691.2	1382.4	2073.6	2764.8	3456	4147.2	4838.4	5529.6	6220.8	6912	3456.0
Total N replaced	t N yr^{-1}	0	4908	9815.04	14722.56	19630.08	24537.6	29445.12	34352.64	39260.16	44167.68	49075.2	24537.6
N_2O avoided (tN yr)	t N_2O-N yr^{-1}	0	68.7	137.4	206.1	274.8	343.5	412.2	480.9	549.6	618.3	687.1	343.5

N_2O Abatement in CO_2 equivalents	kt CO_2e yr^{-1}	0.0	28.6	57.2	85.8	114.4	143.1	171.7	200.3	228.9	257.5	286.1	143.1
Extra SOC -mean from DAYCENT	t CO_2e yr^{-1}	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SOC	kt CO_2e yr^{-1}	0	37.9	75.7	113.6	151.5	189.4	227.2	265.1	303.0	340.8	378.7	189.4
Pathway 1 Costs												
Cost (low)	Unit		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Price clover seed 5kg per ha	€17.4 per kg		€4,107,096	€8,214,192	€12,321,288	€16,428,384	€20,535,480	€24,642,576	€28,749,672	€32,856,768	€36,963,864	€41,070,960	€22,589,028
Fuel 2.5l per ha	€0.53/litre		€62,551	€125,101	€187,652	€250,202	€312,753	€375,304	€437,854	€500,405	€562,955	€625,506	€344,028
Fertiliser clover saving	€1.2 per kg N		€5,889,024	€11,778,048	€17,667,072	€23,556,096	€29,445,120	€35,334,144	€41,223,168	€47,112,192	€53,001,216	€58,890,240	€32,389,632
Total net cost	**€ per year**		**-€739,332**	**-€1,478,665**	**-€2,217,997**	**-€2,957,329**	**-€3,696,661**	**-€4,435,994**	**-€5,175,326**	**-€5,914,658**	**-€6,653,991**	**-€7,393,323**	**-€4,066,328**
Euro per tonne (N_2O)	**€ per tCO2e**		**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€25.84**	**-€26**
Total net cost (SOC)	**€ per year**		**-€980,045**	**-€1,960,090**	**-€2,940,135**	**-€3,920,180**	**-€4,900,226**	**-€5,880,271**	**-€6,860,316**	**-€7,840,361**	**-€8,820,406**	**-€9,800,451**	**-€5,390,248**
Euro per tonne (SOC)	**€ per tCO2e**		**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**	**-€25.88**
Cost (high)	Unit		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Price clover seed 5kg per ha	€19.4 per kg		€4,579,176	€9,158,352	€13,737,528	€18,316,704	€22,895,880	€27,475,056	€32,054,232	€36,633,408	€41,212,584	€45,791,760	€25,185,468
Fuel 2.5l per ha	€1.3/litre		€153,426	€306,852	€460,278	€613,704	€767,130	€920,556	€1,073,982	€1,227,408	€1,380,834	€1,534,260	€843,843
Fertiliser clover saving	€2.6 per kg N		€12,759,552	€25,519,104	€38,278,656	€51,038,208	€63,797,760	€76,557,312	€89,316,864	€102,076,416	€114,835,968	€127,595,520	€70,177,536
Total net cost	**€ per year**		**-€3,451,589**	**-€6,903,177**	**-€10,354,766**	**-€13,806,354**	**-€17,257,943**	**-€20,709,531**	**-€24,161,120**	**-€27,612,708**	**-€31,064,297**	**-€34,515,885**	**-€18,983,737**
Euro per tonne (N_2O)	**€ per tCO2e**		**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€120.64**	**-€121**
Total net cost (SOC)	**€ per year**		**-€4,575,362**	**-€9,150,723**	**-€13,726,085**	**-€18,301,446**	**-€22,876,808**	**-€27,452,169**	**-€32,027,531**	**-€36,602,892**	**-€41,178,254**	**-€45,753,615**	**-€25,164,488**
Euro per tonne (SOC)	**€ per tCO2e**		**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€120.81**	**-€121**
Pathway 2 Costs												
Cost (low)	Unit		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean

Price clover seed 5kg per ha	€17.4 per kg		€6,589,728	€13,179,456	€19,769,184	€26,358,912	€32,948,640	€39,538,368	€46,128,096	€52,717,824	€59,307,552	€65,897,280	€36,243,504
Fuel 2.5l per ha	€0.53/litre		€100,361	€200,722	€301,082	€401,443	€501,804	€602,165	€702,526	€802,886	€903,247	€1,003,608	€551,984
Fertiliser clover saving	€1.2 per kg N		€5,889,024	€11,778,048	€17,667,072	€23,556,096	€29,445,120	€35,334,144	€41,223,168	€47,112,192	€53,001,216	€58,890,240	€32,389,632
Total net cost	**€ per year**		**€344,458**	**€688,916**	**€1,033,374**	**€1,377,831**	**€1,722,289**	**€2,066,747**	**€2,411,205**	**€2,755,663**	**€3,100,121**	**€3,444,579**	**€1,894,518**
Euro per tonne (N_2O)	**€ per tCO2e**		**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12.04**	**€12**
Total net cost (SOC)	**€ per year**		**€456,607**	**€913,214**	**€1,369,821**	**€1,826,428**	**€2,283,035**	**€2,739,642**	**€3,196,249**	**€3,652,855**	**€4,109,462**	**€4,566,069**	**€2,511,338**
Euro per tonne (SOC)	**€ per tCO2e**		**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**	**€12.06**
Cost (high)	Unit		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Price clover seed 5kg per ha	€19.4 per kg		€7,347,168	€14,694,336	€22,041,504	€29,388,672	€36,735,840	€44,083,008	€51,430,176	€58,777,344	€66,124,512	€73,471,680	€40,409,424
Fuel 2.5l per ha	€1.3/litre		€149,760	€299,520	€449,280	€599,040	€748,800	€898,560	€1,048,320	€1,198,080	€1,347,840	€1,497,600	€823,680
Fertiliser clover saving	€2.6 per kg N		€12,759,552	€25,519,104	€38,278,656	€51,038,208	€63,797,760	€76,557,312	€89,316,864	€102,076,416	€114,835,968	€127,595,520	€70,177,536
Total net cost	**€ per year**		**-€2,262,928**	**-€4,525,857**	**-€6,788,785**	**-€9,051,713**	**-€11,314,642**	**-€13,577,570**	**-€15,840,498**	**-€18,103,427**	**-€20,366,355**	**-€22,629,283**	**-€12,446,106**
Euro per tonne (N_2O)	**€ per tCO2e**		**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79.09**	**-€79**
Total net cost (SOC)	**€ per year**		**-€2,999,696**	**-€5,999,391**	**-€8,999,087**	**-€11,998,783**	**-€14,998,478**	**-€17,998,174**	**-€20,997,870**	**-€23,997,565**	**-€26,997,261**	**-€29,996,957**	**-€16,498,326**
Euro per tonne (SOC)	**€ per tCO2e**		**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**	**-€79.21**

Table A1.8: Overview of Modelling Assumptions Used and Results for Phosphorus Impact on N_2O emissions

Pathway 1													
N2O from agricultural soils		Unit	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
(after all measures implemented)	N2O Grazing	kt N_2O-N yr^{-1}	4.523	4.555	4.481	4.438	4.464	4.493	4.515	4.547	4.578	4.605	4.628
	Indirect	kt N_2O-N yr^{-1}	0.758	0.770	0.747	0.734	0.749	0.757	0.637	0.642	0.644	0.646	0.661
	manure	kt N_2O-N yr^{-1}	2.528	2.563	2.509	2.489	2.501	2.508	2.508	2.514	2.520	2.525	2.739
	fertiliser	kt N_2O-N yr^{-1}	4.903	4.582	4.418	4.217	3.973	3.727	3.502	3.272	3.045	2.826	2.672
	Total N_2O	kt N_2O-N yr^{-1}	**12.712**	**12.470**	**12.155**	**11.878**	**11.687**	**11.486**	**11.162**	**10.975**	**10.787**	**10.602**	**10.700**
Proportion of soils at P index 1 or 2	Index1		30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
	Index 2		27%	27%	27%	27%	27%	27%	27%	27%	27%	27%	27%
Grassland	Total hectares		4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700	4,091,700
	Area Index 1	ha	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510
	Area Index 2	ha	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759
	Uptake	fraction	0	0	0.0113	0.0250	0.0375	0.0500	0.0750	0.1000	0.1250	0.1375	0.1500
	Uptake	fraction	0	0	0.0113	0.0250	0.0375	0.0500	0.0750	0.1000	0.1250	0.1375	0.1500
Index1	Area impacted	ha	0	0	13809	30688	46032	61376	92063	122751	153439	168783	184127
Index2	Area impacted	ha	0	0	12429	27619	41428	55238	82857	110476	138095	151904	165714
Index1	Redn in N2O	fraction	0	0	0	0	0	0.1	0.1	0.1	0.2	0.2	0.2
Index2	Redn in N2O	fraction	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1
Reduction in N2O		kt N_2O-N yr^{-1}	0.000	0.000	0.000	0.000	0.000	0.017	0.025	0.033	0.081	0.087	0.096
		kt N_2O-N yr^{-1}	0.000	0.000	0.000	0.000	0.000	0.016	0.023	0.030	0.036	0.039	0.043
Reduction in N2O	**Total abatement**	kt CO_2e yr^{-1}	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**13.632**	**19.871**	**26.051**	**48.851**	**52.813**	**58.148**

Cost													
	Extra P required	Index1	0	0	690474	1534388	2301581	1841265	2761898	3682530	4603163	0	0
		Index2	0	0	372856	828569	1242854	1657139	0	0	0	0	0
Low cost scenario	2.62 per kgP				€2,785,926	€6,190,947	€9,286,420	€9,165,817	€7,236,171	€9,648,229	€12,060,286	0	0
High cost scenario	high cost 3.87 per kgP				€4,115,089	€9,144,643	€13,716,964	€13,538,822	€10,688,543	€14,251,391	€17,814,239	0	0
Low	Euro per tonne CO2e												€220.27
High	Euro per tonne CO2e												€325.37
Pathway 2													
Application of N to soils		Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	N2O Grazing	kt N_2O-N yr^{-1}	4.523	4.555	4.481	4.438	4.464	4.493	4.515	4.547	4.578	4.605	4.628
	Indirect	kt N_2O-N yr^{-1}	0.758	0.770	0.747	0.734	0.749	0.757	0.637	0.642	0.644	0.646	0.661
	manure	kt N_2O-N yr^{-1}	2.528	2.563	2.509	2.489	2.501	2.508	2.508	2.514	2.520	2.525	2.739
	fertiliser	kt N_2O-N yr^{-1}	4.903	4.582	4.418	4.217	3.973	3.727	3.502	3.272	3.045	2.826	2.672
	Total N_2O	kt N_2O-N yr^{-1}	12.712	12.470	12.155	11.878	11.687	11.486	11.162	10.975	10.787	10.602	10.700
Proportion of soils at P index 1 or 2	Index1		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Index 2		0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Grassland	Total hectares		4091700	4091700	4091700	4091700	4091700	4091700	4091700	4091700	4091700	4091700	4091700
	Area Index 1	ha	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510	1227510
	Area Index 2	ha	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759	1104759
	Uptake	fraction	0	0	0.01125	0.03	0.075	0.11	0.15	0.2	0.25	0.275	0.3
	Uptake	fraction	0	0	0.01125	0.03	0.075	0.11	0.15	0.2	0.25	0.275	0.3
Index1	Area impacted	ha	0	0	13809	36825	92063	135026	184127	245502	306878	337565	368253
Index2	Area impacted	ha	0	0	12429	33143	82857	121523	165714	220952	276190	303809	331428

Index1	Redn in N2O	fraction	0	0	0	0	0	0.1	0.1	0.1	0.2	0.2	0.2
Index2	Redn in N2O	fraction	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1
Reduction in N2O		kt N_2O-N yr^{-1}	0	0	0	0	0	0.038	0.050	0.066	0.162	0.175	0.193
		kt N_2O-N yr^{-1}	0	0	0	0	0	0.034	0.045	0.059	0.073	0.079	0.087
Reduction in N2O	**Total abatement**	**kt CO_2e yr^{-1}**	**0**	**0**	**0**	**0**	**0**	**29.990**	**39.742**	**52.102**	**97.702**	**105.626**	**116.295**
Cost													
	Extra P required	Index1	0	0	690474.375	1841265	4603162.5	4050783	5523795	7365060	9206325	0	0
		Index2	0	0	372856.1625	994283.1	2485707.75	3645704.7	0	0	0	0	0
Low cost scenario	2.62 per kgP				€2,785,926	€7,429,136	€18,572,840	€20,164,798	€14,472,343	€19,296,457	€24,120,572	0	0
High cost scenario	high cost 3.87 per kgP				€4,115,089	€10,973,571	€27,433,928	€29,785,407	€21,377,087	€28,502,782	€35,628,478	0	0
Low	Abatement Cost	€ $t^{-1}CO_2e$											€207.45
High	Abatement Cost	€ $t^{-1}CO_2e$											€306.42

Table A1.9: Overview of Modelling Assumptions Used and Results for Reduction in Crude Protein

Business as Usual (BAU) - Cows	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Dairy Cows	000' head	1511.9	1554.9	1599.8	1616.6	1608.6	1608.9	1623.7	1643.4	1662.9	1679.3	1691.8	1618.3
Other Cows	000' head	953.0	915.0	892.8	847.8	802.6	764.4	735.1	709.0	682.9	657.7	632.0	781.1
Cattle < 1 yrs	000' head	2117.1	2145.9	2129.7	2087.4	2143.6	2165.7	2141.4	2111.1	2082.3	2069.0	2054.2	2113.4
Cattle 1 - 2 yrs	000' head	1432.8	1598.2	1437.9	1409.4	1446.8	1461.5	1445.4	1425.3	1406.4	1397.4	1387.9	1440.8
Cattle > 2 yrs	000' head	667.9	589.5	577.7	566.2	580.9	586.7	580.4	572.6	565.3	561.7	558.2	582.5
Bulls	000' head	51.0	49.3	49.5	47.2	44.8	42.3	40.1	38.0	35.8	33.5	31.1	42.0
Dairy Heifers	000' head	330.5	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3	313.7
Other Heifers	000' head	156.7	136.4	138.1	130.6	124.3	119.6	116.9	114.4	111.5	108.2	104.7	123.8
N excretion rates													
Dairy Cows	kg N hd^{-1} yr^{-1}	109.8	111.0	112.2	113.4	114.7	115.9	117.2	118.5	119.8	121.1	122.4	116.0
Other Cows	kg N hd^{-1} yr^{-1}	74.3	74.3	74.3	74.3	74.3	74.3	74.3	74.3	74.3	74.3	74.3	74.3
Cattle < 1 yrs	kg N hd^{-1} yr^{-1}	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1	34.1
Cattle 1 - 2 yrs	kg N hd^{-1} yr^{-1}	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
Cattle > 2 yrs	kg N hd^{-1} yr^{-1}	45.6	45.6	45.6	45.6	45.6	45.6	45.6	45.6	45.6	45.6	45.6	45.6
Bulls	kg N hd^{-1} yr^{-1}	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7
Dairy Heifers	kg N hd^{-1} yr^{-1}	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4	72.4
Other Heifers	kg N hd^{-1} yr^{-1}	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6	76.6
Days Housed													
Dairy Cows	days yr^{-1}	121.7	121.7	121.7	121.7	121.7	121.7	121.7	121.7	121.7	121.7	121.7	122

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Other Cows	days yr^{-1}	152.9	152.9	152.9	152.9	152.9	152.9	152.9	152.9	152.9	152.9	152.9	153
Cattle < 1 yrs	days yr^{-1}	147	147	147	147	147	147	147	147	147	147	147	147
Cattle 1 - 2 yrs	days yr^{-1}	148	148	148	148	148	148	148	148	148	148	148	148
Cattle > 2 yrs	days yr^{-1}	148.5	148.5	148.5	148.5	148.5	148.5	148.5	148.5	148.5	148.5	148.5	149
Bulls	days yr^{-1}	155	155	155	155	155	155	155	155	155	155	155	155
Dairy Heifers	days yr^{-1}	149	149	149	149	149	149	149	149	149	149	149	149
Other Heifers	days yr^{-1}	149	149	149	149	149	149	149	149	149	149	149	149
Frac slurry housing													
Dairy Cows	Percentage	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%
Other Cows	Percentage	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%	82%
Cattle < 1 yrs	Percentage	56%	56%	56%	56%	56%	56%	56%	56%	56%	56%	56%	56%
Cattle 1 - 2 yrs	Percentage	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%	86%
Cattle > 2 yrs	Percentage	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Bulls	Percentage	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%
Dairy Heifers	Percentage	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%
Other Heifers	Percentage	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%	88%
Frac solid housing													
Dairy Cows	Percentage	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Other Cows	Percentage	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Cattle < 1 yrs	Percentage	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%	29%
Cattle 1 - 2 yrs	Percentage	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Cattle > 2 yrs	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bulls	Percentage	14%	14%	14%	14%	14%	14%	14%	14%	14%	14%	14%	14%
Dairy Heifers	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Other Heifers	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
N ex in slurry housing	t N yr^{-1}	152296	155026	152671	151215	151744	151922	151653	151504	151392	151594	151601	152056
TAN ex slurry housing	t NH_4-N yr^{-1}	91378	93016	91603	90729	91047	91153	90992	90902	90835	90956	90961	91234
N ex on hard standing	t N yr^{-1}	15282	15606	15211	14883	15072	15105	14924	14721	14526	14411	14283	14911
TAN ex on hard standing	t NH_4-N yr^{-1}	9169	9364	9127	8930	9043	9063	8954	8833	8716	8646	8570	8947
N ex yards	t N yr^{-1}	17332	17978	18523	18831	19133	19555	20024	20501	20978	21450	21913	19656
TAN ex yard	t NH_4-N yr^{-1}	10399	10787	11114	11298	11480	11733	12014	12300	12587	12870	13148	11794
Direct N2O Slurry Storage EF	kg N_2O kg^{-1} N	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
Direct N2O Solid Storage EF	kg N_2O kg^{-1} N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Direct N2O Spreading EF	kg N_2O kg^{-1} N	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
N2O kt N yr-1 (Slurry storage)	tN_2O-N yr^{-1}	304.6	310.1	305.3	302.4	303.5	303.8	303.3	303.0	302.8	303.2	303.2	304.1
N2O (FYM storage)	tN_2O-N yr^{-1}	152.8	156.1	152.1	148.8	150.7	151.1	149.2	147.2	145.3	144.1	142.8	149.1
Total storage kt N yr-1	tN_2O-N yr^{-1}	457.4	466.1	457.5	451.3	454.2	454.9	452.5	450.2	448.0	447.3	446.0	453.2
Direct N2O Spreading	tN_2O-N yr^{-1}	576.6	586.6	577.5	574.8	578.6	581.7	583.5	586.7	589.8	592.7	595.4	584.0
Ammonia													
Slurry Housing EF	kg NH_3-N kg^{-1} N	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	
Solid Housing EF	kg NH_3-N kg^{-1} N	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Solid Housing EF- Calves	kg NH_3-N kg^{-1} N	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	
Yard EF	kg NH_3-N kg^{-1} N	0.225	0.225	0.225	0.225	0.225	0.225	0.225	0.225	0.225	0.225	0.225	
% Covered store		67%	67%	67%	67%	67%	67%	67%	67%	67%	67%	67%	67%
NH3 EF - covered slurry	kg NH_3-N kg^{-1} N	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
NH3 EF - uncovered slurry	kg NH_3-N kg^{-1} N	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Solid Storage EF	kg NH_3-N kg^{-1} N	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
NH3 Housing (slurry)	$tNH_3N\ yr^{-1}$	25184	25566	25044	24866	24999	25081	25096	25181	25257	25323	25379	25180
NH3 Housing (FYM)	$tNH_3N\ yr^{-1}$	2180	2195	2119	2085	2086	2077	2059	2048	2037	2024	2011	2084
NH3 Yard	$tNH_3N\ yr^{-1}$	2340	2427	2501	2542	2583	2640	2703	2768	2832	2896	2958	2654
NH3 (Slurry storage)	$tNH_3N\ yr^{-1}$	5360	5455	5374	5350	5386	5416	5434	5466	5497	5525	5551	5438
NH3 (Solid storage)	$tNH_3N\ yr^{-1}$	5704	5755	5554	5468	5493	5476	5424	5399	5370	5340	5308	5481
Total slurry N applied to field	t N yr^{-1}	134922	137284	135235	134635	135518	136263	136721	137519	138278	138983	139636	136818
Total slurry TAN applied to field	t NH_4-N yr^{-1}	74132	75434	74319	73994	74482	74895	75152	75596	76018	76410	76773	75200
Total solid N applied to field	t N yr^{-1}	19430	19592	18952	18651	18714	18645	18467	18372	18268	18157	18039	18662
Total solid TAN applied to field	t NH_4-N yr^{-1}	5215	5262	5078	4999	5022	5006	4959	4936	4910	4882	4853	5011
Slurry spreading NH3-N	$tNH_3N\ yr^{-1}$	18128	18447	18174	18095	18214	18315	18378	18486	18590	18685	18774	18390
Solid spreading NH3-N	$tNH_3N\ yr^{-1}$	3562	3594	3468	3415	3430	3419	3387	3371	3354	3335	3315	3423
Total NH3-N	$tNH_3N\ yr^{-1}$	62459	63438	62234	61821	62190	62423	62482	62719	62936	63128	63297	62648

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
EF4 GASM	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Indirect N2O volatilisation	tN_2O-N yr^{-1}	624.6	634.4	622.3	618.2	621.9	624.2	624.8	627.2	629.4	631.3	633.0	626.5
Frac Leach	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
EF5 Leached N	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
N leached	tN_2O-N yr^{-1}	15435	15688	15419	15329	15423	15491	15519	15589	15655	15714	15768	15548
Indirect N2O Leaching	tN_2O-N yr^{-1}	116	118	116	115	116	116	116	117	117	118	118	116.6
Total N2O-N	tN_2O-N yr^{-1}	1774	1805	1773	1759	1770	1777	1777	1781	1785	1789	1793	1780
Total N2O	*kt CO_2e yr^{-1}*	*739*	*752*	*738*	*733*	*737*	*740*	*740*	*742*	*743*	*745*	*747*	*741.4*
BAU - Pigs		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Gilts in Pig	000 head	20.50	20.95	19.64	18.98	18.68	18.52	18.44	18.43	18.47	18.53	18.59	19.07
Gilts not yet Served	000 head	16.25	16.85	15.81	15.29	15.05	14.92	14.86	14.85	14.88	14.93	14.98	15.33
Sows in Pig	000 head	79.15	81.85	79.39	77.18	75.87	75.17	74.85	74.79	74.95	75.21	75.47	76.72
Other Sows for Breeding	000 head	28.95	28.15	27.53	26.64	26.26	26.06	25.96	25.95	26.00	26.08	26.16	26.70
Boars	000 head	1.00	1.10	0.89	0.83	0.81	0.80	0.80	0.80	0.80	0.80	0.81	0.86
Pigs 20 Kg +	000 head	1071.4	1084.0	1068.8	1077.4	1081.1	1072.4	1067.0	1063.7	1062.0	1061.8	1062.4	1070.2
Pigs Under 20 Kg	000 head	438.15	471.00	463.92	437.53	438.54	434.88	432.70	431.43	430.89	430.96	431.32	440.1
N excretion													
Gilts in Pig	kg N hd^{-1} yr^{-1}	20	20	20	20	20	20	20	20	20	20	20	20
Gilts not yet Served	kg N hd^{-1} yr^{-1}	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9
Sows in Pig	kg N hd^{-1} yr^{-1}	20	20	20	20	20	20	20	20	20	20	20	20
Other Sows for Breeding	kg N hd^{-1} yr^{-1}	20	20	20	20	20	20	20	20	20	20	20	20

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Boars	kg N hd^{-1} yr^{-1}	16	16	16	16	16	16	16	16	16	16	16	16
Pigs 20 Kg +	kg N hd^{-1} yr^{-1}	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9
Pigs Under 20 Kg	kg N hd^{-1} yr^{-1}	3	3	3	3	3	3	3	3	3	3	3	3
N excreted in housing	t N yr^{-1}	13908	14177	13916	13835	13829	13715	13649	13613	13601	13608	13623	13771
TAN ex in housing	t NH_4-N yr^{-1}	9736	9924	9741	9684	9680	9601	9554	9529	9521	9526	9536	9639
Direct N_2O Slurry Storage EF	kg N_2O kg^{-1} N	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.00
Direct N_2O Spreading EF	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Direct N_2O Slurry storage	t N2O-N yr-1	27.82	28.35	27.83	27.67	27.66	27.43	27.30	27.23	27.20	27.22	27.25	27.54
Direct N_2O Landspread	t N2O-N yr-1	85.67	87.13	87.10	87.37	87.80	88.34	88.93	89.57	90.21	90.87	91.55	88.60
Housing NH3 EF													
Gilts in Pig	kg NH_3-N kg^{-1} N	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	
Gilts not yet Served	kg NH_3-N kg^{-1} N	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	
Sows in Pig	kg NH_3-N kg^{-1} N	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	
Other Sows for Breeding	kg NH_3-N kg^{-1} N	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	
Boars	kg NH_3-N kg^{-1} N	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	
Pigs 20 Kg +	kg NH_3-N kg^{-1} N	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	
Pigs Under 20 Kg	kg NH_3-N kg^{-1} N	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	

Business as Usual (BAU) - Cows	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Ammonia Housing	t NH3-N yr-1	2846.5	2892.4	2840.7	2838.4	2840.1	2816.9	2803.2	2795.5	2792.5	2793.4	2796.1	2823.3
Slurry storage type													
Covered	percentage	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%
Uncovered	percentage	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%
Storage emission factor - slurry (proportion of TAN)													
Ammonia - covered store	percentage	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	0.13
Ammonia - uncovered store	percentage	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	0.52
Ammonia Storage	t NH_3-N yr^{-1}	1312	1334	1334	1338	1345	1353	1362	1372	1381	1391	1402	1357
N applied to field	t N yr^{-1}	9713	9878	9875	9906	9954	10015	10083	10154	10227	10302	10379	10044
TAN applied to field	t NH_4-N yr^{-1}	5958	6060	6058	6077	6107	6144	6186	6229	6274	6320	6367	6162
Landspread ammonia EF	kg NH_3-N kg^{-1} N	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%
Ammonia from Landspreading	t NH_3-N yr^{-1}	1145	1165	1165	1168	1174	1181	1189	1198	1206	1215	1224	1185
Total Ammonia	t NH_3-N yr^{-1}	5304	5392	5339	5345	5359	5351	5354	5365	5380	5400	5422	5365
N_2O from volatilisation EF4		1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
Indirect N_2O volatilisation	tN_2O-N yr^{-1}	53.04	53.92	53.39	53.45	53.59	53.51	53.54	53.65	53.80	54.00	54.22	53.65
Frac Leach	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	0.10
EF5 Leached N		1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
N leached	tN_2O-N yr^{-1}	971	988	987	991	995	1002	1008	1015	1023	1030	1038	1004
Indirect N2O Leaching (CO2 equivalents)	kt CO_2e yr^{-1}	7.28	7.41	7.41	7.43	7.47	7.51	7.56	7.62	7.67	7.73	7.78	7.53
Total N_2O-N	tN_2O-N yr^{-1}	173.8	176.8	175.7	175.9	176.5	176.8	177.3	178.1	178.9	179.8	180.8	177.32

Business as Usual (BAU) - Cows	**Unit**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Total N_2O (CO2 equivalents)	*kt CO_2e yr^{-1}*	*72.38*	*73.63*	*73.18*	*73.26*	*73.51*	*73.62*	*73.85*	*74.15*	*74.49*	*74.88*	*75.29*	*73.84*

Pathway 1-Bovines													
Crude protein reduction	Percentage	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Uptake	Percentage	2%	4%	10%	18%	27%	33%	35%	37%	38%	39%	40%	26%
N excreted in slurry housing	t N yr^{-1}	151911	154036	150468	147152	145773	144712	143866	143272	142909	142961	142781	146349
TAN excreted in slurry housing	t NH_4-N yr^{-1}	91147	92421	90281	88291	87464	86827	86319	85963	85745	85777	85669	87809
N ex on hard standing	t N yr^{-1}	15243	15506	14992	14483	14479	14389	14158	13921	13712	13590	13452	14357
TAN ex on hard standing	t NH_4-N yr^{-1}	9146	9304	8995	8690	8687	8633	8495	8353	8227	8154	8071	8614
N ex yards	t N yr^{-1}	17332	17978	18523	18831	19133	19555	20024	20501	20978	21450	21913	19656
TAN ex yard	t NH_4-N yr^{-1}	10399	10787	11114	11298	11480	11733	12014	12300	12587	12870	13148	11794
Direct N2O Slurry Storage EF	Percentage	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.0
Direct N2O Solid Storage EF	Percentage	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.0
Direct N2O Spreading EF	Percentage	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.0
N2O (Slurry storage)	tN_2O-N yr^{-1}	303.8	308.1	300.9	294.3	291.5	289.4	287.7	286.5	285.8	285.9	285.6	292.7
N2O (FYM storage)	tN_2O-N yr^{-1}	152.4	155.1	149.9	144.8	144.8	143.9	141.6	139.2	137.1	135.9	134.5	143.6
Total storage kt N yr-1	tN_2O-N yr^{-1}	456.3	463.1	450.9	439.1	436.3	433.3	429.3	425.8	422.9	421.8	420.1	436.3
Direct N2O Spreading	tN_2O-N yr^{-1}	575.3	583.2	570.1	561.2	558.5	557.3	557.1	559.5	562.2	564.9	567.4	565.2
NH3 Housing (slurry)	tNH_3-N yr^{-1}	25121	25403	24683	24198	24015	23891	23808	23848	23904	23961	24012	24258
NH3 Housing (FYM)	tNH_3-N yr^{-1}	2175	2181	2088	2029	2004	1978	1953	1940	1927	1915	1902	2008
NH3 Yard	tNH_3-N yr^{-1}	2340	2427	2501	2542	2583	2640	2703	2768	2832	2896	2958	2654
NH3 (Slurry storage)	tNH_3-N yr^{-1}	5348	5424	5305	5224	5199	5190	5190	5213	5240	5267	5292	5263
NH3 (Solid storage)	tNH_3-N yr^{-1}	5689	5718	5474	5321	5277	5216	5146	5113	5083	5053	5022	5283

Total slurry N applied to field	t N yr^{-1}	134617	136501	133504	131434	130806	130561	130548	131133	131799	132459	133086	132404
Total slurry TAN applied to field	t NH_4-N yr^{-1}	73965	75005	73370	72241	71901	71772	71771	72097	72468	72836	73186	72783
Total solid N applied to field	t N yr^{-1}	19385	19477	18704	18195	18043	17839	17602	17484	17375	17265	17152	18047
Total solid TAN applied to field	t NH_4-N yr^{-1}	5202	5228	5005	4865	4824	4769	4704	4674	4647	4620	4592	4830
Slurry spreading NH3-N	tNH_3-N yr^{-1}	18088	18342	17942	17666	17583	17551	17551	17631	17722	17812	17897	17799
Solid spreading NH3-N	tNH_3-N yr^{-1}	3553	3571	3418	3323	3295	3257	3213	3193	3174	3155	3136	3299
Total NH3-N	tNH_3-N yr^{-1}	62313	63065	61412	60303	59955	59723	59563	59704	59882	60058	60220	60564
N2O from volatilisation EF4	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.0
Indirect N2O volatilisation	tN_2O-N y^{r-1}	623.1	630.7	614.1	603.0	599.5	597.2	595.6	597.0	598.8	600.6	602.2	605.6
Frac Leach	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
EF5 Leached N	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
N leached	tN yr^{-1}	15400	15598	15221	14963	14885	14840	14815	14862	14917	14972	15024	15045.2
Indirect N2O Leaching	tN_2O-N yr^{-1}	115.5	117.0	114.2	112.2	111.6	111.3	111.1	111.5	111.9	112.3	112.7	112.8
Total N2O-N	tN_2O-N yr^{-1}	1770.1	1794.0	1749.3	1715.6	1706.0	1699.2	1693.2	1693.7	1695.8	1699.6	1702.4	1719.9
Total N2O	kt CO_2e yr^{-1}	737.1	747.1	728.4	714.4	710.4	707.6	705.1	705.3	706.2	707.8	708.9	716.2
Reduction	**kt CO_2e yr^{-1}**	**1.74**	**4.47**	**9.87**	**18.21**	**26.81**	**32.41**	**35.00**	**36.36**	**36.99**	**37.30**	**37.57**	**25.2**

Pathway 1 Pigs	1% reduction in CP = 7.5% reduction in Nex	Ball et al. 2013, 2016											
Crude Protein Reduction	Percentage	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Uptake	Percentage	0%	4%	8%	12%	16%	20%	24%	28%	32%	36%	40%	20%
Total N excreted	t N yr^{-1}	13908	14027	13906	13833	13785	13752	13728	13708	13688	13669	13650	13787
Total TAN excreted	t NH_4-N yr^{-1}	9736	9819	9734	9683	9649	9627	9610	9596	9582	9568	9555	9651
Direct N_2O Slurry Storage EF	kg N_2O kg^{-1} N	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.20%	0.2%
Direct N_2O Spreading EF	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1.0%
Direct N_2O Slurry storage	t N_2O-N yr^{-1}	27.82	28.05	27.81	27.67	27.57	27.50	27.46	27.42	27.38	27.34	27.30	27.57
Direct N_2O Landspread	t N_2O-N yr^{-1}	85.67	86.20	85.23	84.55	84.03	83.59	83.20	82.83	82.46	82.09	81.71	83.78
Ammonia from Housing	tNH_3-N yr^{-1}	2847	2868	2792	2765	2743	2696	2659	2628	2601	2578	2556	2703
Slurry storage type													
Covered	Percentage	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	
Uncovered	Percentage	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	
Storage emission factor - slurry (proportion of TAN)													
NH3 - covered store	kg NH_3N kg^{-1} N	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	0.13
NH3 - uncovered store	kg NH_3N kg^{-1} N	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	0.52
Ammonia from Storage	tNH_3-N yr^{-1}	1312	1320	1305	1295	1287	1281	1275	1269	1264	1258	1253	1284

N applied to field	t N yr^{-1}	9713	9772	9663	9587	9527	9478	9433	9391	9349	9307	9265	9499
TAN applied to field	t NH_4-N yr^{-1}	5958	5995	5929	5883	5847	5817	5790	5765	5739	5714	5689	5830
Landspread EF	*kg NH_3N kg^{-1} N*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*	*19%*
NH3 Landspread	tNH_3-N yr^{-1}	1145	1153	1140	1131	1124	1118	1113	1108	1104	1099	1094	1121
Total NH3	tNH_3-N yr^{-1}	5304	5340	5285	5250	5224	5204	5187	5172	5157	5142	5126	5217
EF4 GASM	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
Indirect N2O volatilisation	tN_2O-N yr^{-1}	53.04	53.40	52.85	52.50	52.24	52.04	51.87	51.72	51.57	51.42	51.26	52.17
Frac Leach	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	0.10
EF5 Leached N	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
N leached	tN yr^{-1}	971.3	977.2	966.3	958.7	952.7	947.8	943.3	939.1	934.9	930.7	926.5	949.9
Indirect N2O Leaching	tN_2O-N yr^{-1}	7.28	7.33	7.25	7.19	7.15	7.11	7.08	7.04	7.01	6.98	6.95	7.12
Total N2O-N	tN_2O-N yr^{-1}	173.8	175.0	173.1	171.9	171.0	170.2	169.6	169.0	168.4	167.8	167.2	170.65
Total N2O	kt CO_2e yr^{-1}	72.4	72.9	71.7	71.1	70.6	69.9	69.4	69.0	68.5	68.1	67.8	70.13
Reduction	kt CO_2e yr^{-1}	0.00	0.73	1.46	2.19	2.93	3.67	4.43	5.19	5.96	6.74	7.53	3.71
Total reduction (Cows and Pigs)	**kt CO2e yr-1**	**1.74**	**5.20**	**11.33**	**20.40**	**29.74**	**36.08**	**39.43**	**41.55**	**42.94**	**44.04**	**45.10**	**31.6**

Pathway 2 Bovines													
Crude protein reduction	Percentage	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Uptake	Percentage	2%	4%	11%	22%	34%	46%	58%	74%	83%	86%	90%	46%
N ex in slurry housing	t N yr^{-1}	151908	154022	150329	146448	144126	141719	138929	135161	132997	132513	131760	141810
TAN ex slurry housing	t NH_4-N yr^{-1}	91145	92413	90197	87869	86476	85031	83358	81097	79798	79508	79056	85086
N ex on hard standing	t N yr^{-1}	15243	15505	14978	14414	14315	14091	13672	13133	12761	12597	12414	13920
TAN ex on hard standing	t NH_4-N yr^{-1}	9146	9303	8987	8648	8589	8455	8203	7880	7657	7558	7448	8352
N ex yards	t N yr^{-1}	17332	17978	18523	18831	19133	19555	20024	20501	20978	21450	21913	19656
TAN ex yard	t NH_4-N yr^{-1}	10399	10787	11114	11298	11480	11733	12014	12300	12587	12870	13148	11794
Direct N2O Slurry Storage EF	Percentage	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
Direct N2O Solid Storage EF	Percentage	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Direct N2O Spreading EF	Percentage	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
N2O kt N yr-1 (Slurry storage)	tN_2O-N yr^{-1}	303.8	308.0	300.7	292.9	288.3	283.4	277.9	270.3	266.0	265.0	263.5	283.6
N2O (FYM storage)	tN_2O-N yr^{-1}	152.4	155.1	149.8	144.1	143.2	140.9	136.7	131.3	127.6	126.0	124.1	139.2
Total storage kt N yr-1	tN_2O-N yr^{-1}	456.2	463.1	450.4	437.0	431.4	424.3	414.6	401.7	393.6	391.0	387.7	422.8
Direct N2O Spreading	tN_2O-N yr^{-1}	575.3	583.2	569.7	559.1	556.7	547.2	542.8	538.4	536.9	537.2	538.7	553.2
NH3 Housing (slurry)	tNH_3-N yr^{-1}	25120	25401	24660	24099	23928	23397	23105	22815	22664	22605	22606	23673
NH3 Housing (FYM)	tNH_3-N yr^{-1}	2175	2181	2086	2021	1996	1937	1895	1856	1828	1807	1791	1961
NH3 Yard	tNH_3-N yr^{-1}	2340	2427	2501	2542	2583	2640	2703	2768	2832	2896	2958	2654
NH3 (Slurry storage)	tNH_3-N yr^{-1}	5348	5423	5301	5205	5183	5096	5056	5017	5005	5010	5025	5152
NH3 (Solid storage)	tNH_3-N yr^{-1}	5689	5718	5469	5299	5258	5108	4994	4891	4819	4767	4728	5158
Total slurry N applied to field	t N yr^{-1}	134615	136491	133394	130959	130390	128194	127185	126188	125859	125967	126353	129600

Total slurry TAN applied to field	t NH_4-N yr^{-1}	73964	75000	73310	71981	71673	70475	69929	69389	69215	69280	69497	71247
Total solid N applied to field	t N yr^{-1}	19385	19476	18688	18127	17984	17504	17131	16797	16557	16378	16239	17660
Total solid TAN applied to field	t NH_4-N yr^{-1}	5201	5228	5000	4845	4807	4670	4566	4472	4406	4358	4323	4716
Slurry spreading NH3-N	tNH_3-N yr^{-1}	18087	18341	17928	17602	17527	17234	17101	16968	16926	16942	16995	17423
Solid spreading NH3-N	tNH_3-N yr^{-1}	3553	3570	3415	3309	3283	3190	3118	3054	3009	2977	2953	3221
Total Ammonia	tNH_3-N yr^{-1}	62312	63060	61360	60077	59758	58602	57973	57370	57083	57003	57057	59241
EF4 GASM	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Indirect N2O volatilisation	tN_2O-N yr^{-1}	623.1	630.6	613.6	600.8	597.6	586.0	579.7	573.7	570.8	570.0	570.6	592.4
Leached N	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
EF5 Leached N	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
N leached	tN_2O-N yr^{-1}	15400	15597	15208	14909	14837	14570	14432	14299	14242	14234	14259	14726
Indirect N2O Leaching	tN_2O-N yr^{-1}	115.5	117.0	114.1	111.8	111.3	109.3	108.2	107.2	106.8	106.8	106.9	110.4
Total N2O-N	tN_2O-N yr^{-1}	1770	1794	1748	1709	1697	1667	1645	1621	1608	1605	1604	1679
Total N2O	kt CO_2e yr^{-1}	737.1	747.0	727.8	711.6	706.7	694.1	685.2	675.0	669.7	668.4	667.9	699.1
Reduction	**kt CO_2e yr^{-1}**	**1.75**	**4.53**	**10.50**	**21.03**	**30.57**	**45.86**	**54.93**	**66.67**	**73.52**	**76.70**	**78.60**	**42.24**
Pathway 2 Pigs													
Crude Protein reduction	Percentage	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	0.03
Uptake	Percentage	0%	8%	16%	24%	32%	40%	48%	56%	64%	72%	80%	0.40
Total N excreted	t N yr^{-1}	13908	13759	13100	12619	12220	11735	11300	10898	10522	10166	9821	11823
Total TAN excreted	t NH_4-N yr^{-1}	9736	9631	9170	8834	8554	8214	7910	7629	7365	7116	6875	8276

Direct N2O Slurry Storage EF	kg N_2O kg^{-1} N	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Direct N2O Spreading EF	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Direct N2O Slurry storage	t N2O-N yr-1	27.82	27.52	26.20	25.24	24.44	23.47	22.60	21.80	21.04	20.33	19.64	23.65
Direct N2O Landspread	t N2O-N yr-1	85.67	84.35	81.58	79.12	76.84	74.67	72.56	70.49	68.44	66.41	64.40	74.96
NH3 Housing	tNH_3-N yr^{-1}	2847	2802	2665	2576	2493	2389	2296	2209	2127	2050	1975	2403
Slurry storage type													
Covered	Percentage	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	87%	
Uncovered	Percentage	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	
Storage emission factor - slurry (proportion of TAN)													
Ammonia - covered store	kg NH_3N kg^{-1} N	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	0.13
Ammonia - uncovered store	kg NH_3N kg^{-1} N	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	0.52
Ammonia from Storage	tNH_3-N yr^{-1}	1312	1292	1250	1213	1178	1145	1113	1082	1051	1020	990	1150
N applied to field	t N yr^{-1}	9713	9563	9249	8971	8713	8467	8228	7994	7762	7532	7305	8500
TAN applied to field	t NH_4-N yr^{-1}	5958	5868	5677	5509	5351	5202	5057	4914	4773	4634	4496	5222
Landspread EF	kg NH_3N kg^{-1} N	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	19%	
Ammonia from Landspreading	tNH_3-N yr^{-1}	1145	1128	1092	1059	1029	1000	972	945	918	891	864	1004
Total Ammonia	tNH_3-N yr^{-1}	5304	5223	5007	4848	4700	4534	4381	4236	4096	3961	3829	4556
N2O from volatilisation EF4	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	
Indirect N2O volatilisation	tN_2O-N yr^{-1}	53.04	52.23	50.07	48.48	47.00	45.34	43.81	42.36	40.96	39.61	38.29	45.56

Leached N	Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	0.10
EF5 Leached N	kg N_2O kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
N leached		971.3	956.3	924.9	897.1	871.3	846.7	822.8	799.4	776.2	753.2	730.5	850.0
Indirect N2O Leaching	tN_2O-N yr^{-1}	7.28	7.17	6.94	6.73	6.53	6.35	6.17	6.00	5.82	5.65	5.48	6.37
Total N2O-N	tN_2O-N yr^{-1}	173.8	171.3	164.8	159.6	154.8	149.8	145.1	140.6	136.3	132.0	127.8	150.5
Total N2O	kt CO_2e yr^{-1}	72.38	71.32	68.62	66.45	64.47	62.39	60.44	58.57	56.74	54.97	53.23	62.69
Reduction Pig Reduction	kt CO_2e yr^{-1}	0.00	1.58	3.10	4.62	6.10	7.55	8.98	10.40	11.79	13.17	14.53	7.44
Total cow and pig reduction	**kt CO_2e yr^{-1}**	**1.75**	**6.11**	**13.60**	**25.65**	**36.68**	**53.41**	**63.92**	**77.06**	**85.32**	**89.87**	**93.13**	**49.68**

Costs

Costs - Bovines											
Pathway 1	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Uptake	0	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32	0.36	0.4	
Livestock Units '000	5233	5249	5156	5078	5090	5081	5044	5008	4973	4952	4924	
LU uptake '000	0	210	412	609	814	1016	1211	1402	1591	1783	1970	
Cost BAU	€0	€49,973,541	€98,161,078	€145,032,518	€193,827,829	€241,864,001	€288,133,127	€333,757,119	€378,770,306	€424,258,816	€468,751,916	€262,253,025
Mean CP cost reduction	€0	€49,690,077	€97,604,282	€144,209,855	€192,728,385	€240,492,083	€286,498,759	€331,863,959	€376,621,819	€421,852,306	€466,093,029	€260,765,455
Cost	€0	-€283,463	-€556,796	-€822,663	-€1,099,444	-€1,371,918	-€1,634,369	-€1,893,160	-€2,148,487	-€2,406,510	-€2,658,887	-€1,487,570
Pathway 2												
Uptake	0	0	0	0	0	0	1	1	1	1	1	
Livestock Units '000	5233	5252	5101	5039	5049	5042	5015	5004	4991	4976	4957	
LU uptake '000	0	234	538	1091	1741	2326	2890	3708	4165	4301	4456	
Cost	€0	€55,588,767	€127,935,246	€259,660,142	€414,397,303	€553,514,922	€687,812,899	€882,404,769	€991,339,549	€1,023,728,778	€1,060,582,720	€605,696,510
Mean CP cost reduction	€0	€55,273,453	€127,209,563	€258,187,280	€412,046,730	€550,375,237	€683,911,439	€877,399,531	€985,716,404	€1,017,921,913	€1,054,566,810	€602,260,836
Cost	€0	-€315,314	-€725,683	-€1,472,862	-€2,350,573	-€3,139,685	-€3,901,460	-€5,005,237	-€5,623,144	-€5,806,865	-€6,015,910	-€3,435,673
Pigs												
Population (minus piglets) '000 head	1217.2	1236.7	1235.3	1238.8	1244.9	1252.8	1261.7	1271.2	1280.9	1290.8	1300.9	
Uptake Pathway 1	0	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40	
UptakePathway 2	0%	8%	16%	24%	32%	40%	48%	56%	64%	72%	80%	
Pop uptake of measure '000 Pathway 1	0	49.5	98.8	148.7	199.2	250.6	302.8	355.9	409.9	464.7	520.4	

Pop uptake of measure '000 Pathway 2	0	98.9	197.7	297.3	398.4	501.1	605.6	711.9	819.7	929.3	1040.7	560.07
Min cost per head	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58	-€4.58
Max cost per head	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00	€2.00
Min cost Pathway 1	€0	-€226,569	-€452,630	-€680,869	-€912,295	-€1,147,553	-€1,386,846	-€1,630,149	-€1,877,220	-€2,128,204	-€2,383,224	-€1,282,556
Max cost Pathway 1	€0	€98,938	€197,655	€297,323	€398,382	€501,115	€605,610	€711,856	€819,747	€929,347	€1,040,709	€560,068
Min cost Pathway 2	€0	-€453,138	-€905,261	-€1,361,738	-€1,824,589	-€2,295,106	-€2,773,693	-€3,260,299	-€3,754,440	-€4,256,408	-€4,766,449	-€2,565,112
Max cost Pathway 2	€0	€197,877	€395,310	€594,646	€796,764	€1,002,230	€1,211,219	€1,423,711	€1,639,493	€1,858,693	€2,081,419	€1,120,136
Total (Cow/Pig) Low cost Pathway 1	0	-€510,032	-€1,009,427	-€1,503,533	-€2,011,738	-€2,519,471	-€3,021,215	-€3,523,310	-€4,025,707	-€4,534,714	-€5,042,111	-€2,770,126
Total (Cow/Pig) High cost Pathway 1	0	-€184,525	-€359,141	-€525,341	-€701,062	-€870,803	-€1,028,759	-€1,181,305	-€1,328,740	-€1,477,163	-€1,618,178	-€927,502
Total (Cow/Pig) Low cost Pathway 2	0	-€768,452	-€1,630,944	-€2,834,601	-€4,175,162	-€5,434,792	-€6,675,152	-€8,265,536	-€9,377,584	-€10,063,273	-€10,782,359	-€6,000,786
Total (Cow/Pig) High cost Pathway 2	0	-€117,438	-€330,373	-€878,217	-€1,553,809	-€2,137,456	-€2,690,240	-€3,581,526	-€3,983,651	-€3,948,172	-€3,934,492	-€2,315,537
Abatement Cost Pathway 1 (Low Cost)	0	-€98.11	-€89.09	-€73.71	-€67.64	-€69.83	-€76.63	-€84.80	-€93.74	-€102.98	-€111.79	-€86.83
Abatement Cost Pathway 1 (High Cost)	0	-€35.49	-€31.70	-€25.75	-€23.57	-€24.13	-€26.09	-€28.43	-€30.94	-€33.54	-€35.88	-€29.55

Abatement Cost Pathway 2 (Low Cost)	0	-€125.86	-€119.90	-€110.51	-€113.84	-€101.75	-€104.43	-€107.26	-€109.92	-€111.98	-€115.78	-€112.12
Abatement Cost Pathway 2 (High Cost)	0	-€19.23	-€24.29	-€34.24	-€42.36	-€40.02	-€42.09	-€46.48	-€46.69	-€43.93	-€42.25	-€38.16

Table A1.10: Overview of Modelling Assumptions Used and Results for Fertiliser Formulation

Table A1.10a: Overview of Modelling Assumptions Used and Results for urea protected with urease and nitrification inhibitors

	N saving lime	1261.2	3783.5	7567.0	12611.6	17656.3	22700.9	27745.6	32790.2	37834.8	42879.5	
	N saving clover	3162.2	6324.5	9486.7	12649.0	15811.2	18973.4	22135.7	25297.9	28460.2	31622.4	
	N saving LESS	425.4	636.2	1162.9	2317.7	2311.1	2306.0	2302.5	2301.1	2302.1	2305.5	
Pathway 1												
Projected fertiliser use	tN yr^{-1}	**399164**	**343200**	**305621**	**303833**	**323828**	**394800**	**401345**	**407481**	**404039**	**399397**	
Fertiliser required after other measures implemented	tN yr^{-1}	394,315.2	332,455.8	287,404.8	276,254.6	288,049.5	350,819.3	349,160.8	347,092.1	335,442.0	322,590.0	
BAU		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
FCAN	tN yr^{-1}	166320	140228	121226	116523	121498	147974	147274	146402	141488	136067	144025
FUREA	tN yr^{-1}	32993	27818	24048	23115	24102	29354	29215	29042	28067	26992	28571
FNH3SO4	tN yr^{-1}	4517	3808	3292	3165	3300	4019	4000	3976	3843	3695	3912
Fother	tN yr^{-1}	190485	160602	138839	133452	139150	169473	168672	167672	162044	155836	164951
Total	tN yr^{-1}	394315	332456	287405	276255	288049	350819	349161	347092	335442	322590	341459
N2O EF CAN	kg N_2O-N kg^{-1} N	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	
N2O EF UREA	kg N_2O-N kg^{-1} N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
N2O EF KAN	kg N_2O-N kg^{-1} N	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
BAU												
N_2O CAN	tN_2O-N yr^{-1}	2328.48	1963.19	1697.16	1631.32	1700.97	2071.63	2061.84	2049.62	1980.83	1904.93	2,016.4
N_2O UREA	tN_2O-N yr^{-1}	98.98	83.45	72.14	69.34	72.31	88.06	87.65	87.13	84.20	80.98	85.7

N_2O NH3SO4	tN_2O-N yr^{-1}	13.55	11.43	9.88	9.49	9.90	12.06	12.00	11.93	11.53	11.09	11.7
N_2O other	tN_2O-N yr^{-1}	2666.79	2248.43	1943.74	1868.33	1948.10	2372.62	2361.40	2347.41	2268.62	2181.70	2,309.3
Total N_2O emissions	tN_2O-N yr^{-1}	**5107.80**	**4306.50**	**3722.92**	**3578.49**	**3731.27**	**4544.37**	**4522.88**	**4496.09**	**4345.18**	**4178.70**	**4,423.1**
PU uptake urea	percentage	20%	25%	30%	40%	60%	80%	100%	100%	100.00%	100.00%	
PU uptake CAN	percentage	2.00%	8.50%	15.00%	21.50%	28.00%	34.50%	41.00%	47.50%	54.00%	65.00%	
FCAN	tN yr^{-1}	162,993.5	128,308.6	103,041.9	91,470.3	87,478.3	96,922.7	86,891.7	76,860.8	65,084.3	47,623.3	110,185.1
FUREA	tN yr^{-1}	26,394.8	20,863.1	16,833.6	13,869.0	9,640.8	5,870.8	-	-	-	-	13,892.3
FNH_3SO_4	tN yr^{-1}	4,517.1	3,808.5	3,292.4	3,164.6	3,299.8	4,018.8	3,999.8	3,976.1	3,842.7	3,695.4	3,911.6
Fother	tN yr^{-1}	190,484.7	160,601.9	138,838.8	133,452.3	139,150.2	169,472.9	168,671.7	167,672.3	162,044.4	155,835.9	164,950.9
FKAN	tN yr^{-1}	9,925.1	18,873.8	25,398.2	34,298.4	48,480.5	74,534.1	89,597.6	98,582.9	104,470.6	115,435.3	48,518.7
Total Fertiliser	tN yr^{-1}	**394,315.2**	**332,455.8**	**287,404.8**	**276,254.6**	**288,049.5**	**350,819.3**	**349,160.8**	**347,092.1**	**335,442.0**	**322,590.0**	**341,458.6**
N_2O EF CAN	kg N_2O-N kg^{-1} N	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	
N_2O EF UREA	kg N_2O-N kg^{-1} N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
N_2O EF KAN	kg N_2O-N kg^{-1} N	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
N_2O CAN	tN_2O-N yr^{-1}	2281.9	1796.3	1442.6	1280.6	1224.7	1356.9	1216.5	1076.1	911.2	666.7	1190.2
N_2O UREA	tN_2O-N yr^{-1}	79.2	62.6	50.5	41.6	28.9	17.6	0.0	0.0	0.0	0.0	27.8
N_2O NH3SO4	tN_2O-N yr^{-1}	13.6	11.4	9.9	9.5	9.9	12.1	12.0	11.9	11.5	11.1	9.7
N_2O compounds	tN_2O-N yr^{-1}	2666.8	2248.4	1943.7	1868.3	1948.1	2372.6	2361.4	2347.4	2268.6	2181.7	1905.7

N_2O KAN	tN_2O-N yr^{-1}	39.7	75.5	101.6	137.2	193.9	298.1	358.4	394.3	417.9	461.7	192.6
Total N_2O Emissions	tN_2O-N yr^{-1}	**5081.1**	**4194.3**	**3548.3**	**3337.2**	**3405.5**	**4057.3**	**3948.3**	**3829.7**	**3609.2**	**3321.3**	3325.9
Reduction in N_2O-N	tN_2O-N yr^{-1}	26.7	112.2	174.6	241.3	325.7	487.0	574.6	666.4	736.0	857.4	324.1
CO_2e Abated	**kt CO2e yr-1**	**11.1**	**46.7**	**72.7**	**100.5**	**135.6**	**202.8**	**239.3**	**277.5**	**306.5**	**357.1**	**135.0**
extra CO_2 from urea	kt CO2e yr-1	7.3	13.8	18.6	25.2	35.6	54.7	65.7	72.3	76.6	84.7	35.3
Net Reduction	**kt CO2e yr-1**	**3.8**	**32.9**	**54.1**	**75.3**	**100.1**	**148.2**	**173.6**	**205.2**	**229.9**	**272.4**	**99.7**

Pathway 2

N saving lime		1831	5493	10987	18312	25636	32961	40286	47610	54935	62259	
N saving clover		4908	9815	14723	19630	24538	29445	34353	39260	44168	49075	
N saving LESS		425	636	1163	2318	2311	2306	2303	2301	2302	2305	
Pathway 2												
Projected fertiliser use	tN yr^{-1}	399,164	343,200	305,621	303,833	323,828	394,800	401,345	407,481	404,039	399,397	
Fertiliser required after other measures implemented	tN yr^{-1}	392,000	327,255	278,749	263,573	271,343	330,088	324,404	318,310	302,634	285,757	
BAU		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
FCAN	tN yr^{-1}	165343	138034	117575	111174	114451	139229	136832	134261	127650	120531	137878
FUREA	tN yr^{-1}	32800	27382	23324	22054	22704	27619	27144	26634	25322	23910	27351
FNH3SO4	tN yr^{-1}	4491	3749	3193	3019	3108	3781	3716	3646	3467	3273	3745
Fother	tN yr^{-1}	189366	158090	134657	127326	131080	159458	156712	153768	146196	138043	157910
Total Fertiliser Use	tN yr^{-1}	392000	327255	278749	263573	271343	330088	324404	318310	302634	285757	326884
N2O EF CAN	kg N_2O-N kg^{-1} N	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	
N2O EF UREA	kg N_2O-N kg^{-1} N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
N2O EF PU	kg N_2O-N kg^{-1} N	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	

BAU												
N2O CAN	tN_2O-N yr^{-1}	2314.8	1932.5	1646.0	1556.4	1602.3	1949.2	1915.6	1879.7	1787.1	1687.4	1930.3
N2O UREA	tN_2O-N yr^{-1}	98.4	82.1	70.0	66.2	68.1	82.9	81.4	79.9	76.0	71.7	82.1
N2O NH3SO4	tN_2O-N yr^{-1}	13.5	11.2	9.6	9.1	9.3	11.3	11.1	10.9	10.4	9.8	11.2
N2O other	tN_2O-N yr^{-1}	2651.1	2213.3	1885.2	1782.6	1835.1	2232.4	2194.0	2152.8	2046.7	1932.6	2210.7
Total N2O emissions	tN_2O-N yr^{-1}	**5077.8**	**4239.1**	**3610.8**	**3414.2**	**3514.9**	**4275.8**	**4202.2**	**4123.3**	**3920.2**	**3701.6**	**4234.3**
Pathway 2												
PU uptake urea	percentage	20%	25%	30%	40%	60%	80%	100%	100%	100%	100%	
PU uptake CAN	percentage	2%	3%	10%	25%	35%	45%	55%	65%	75%	75%	
PU+NI uptake CAN	percentage									10%	20%	
FCAN	t N yr^{-1}	162036	133893	105817	83380	74393	76576	61574	46991	31912	30133	99418
FUREA	t N yr^{-1}	26240	20537	16327	13232	9082	5524	0	0	0	0	13698
FNH3SO4	t N yr^{-1}	4491	3749	3193	3019	3108	3781	3716	3646	3467	3273	3745
Fother	t N yr^{-1}	189366	158090	134657	127326	131080	159458	156712	153768	146196	138043	157910
F PU	t N yr^{-1}	9867	10987	18755	36615	53680	84749	102401	113904	121059	114308	52113
F PU+DCD	t N yr^{-1}									12765	24106	18436
Total Fertiliser	**t N yr^{-1}**	**392000**	**327255**	**278749**	**263573**	**271343**	**330088**	**324404**	**318310**	**302634**	**285757**	**326884**
N2O EF CAN	kg N_2O-N kg^{-1} N	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	
N2O EF UREA	kg N_2O-N kg^{-1} N	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
N2O EF PU	kg N_2O-N kg^{-1} N	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
N2O EF PU+DCD	kg N_2O-N kg^{-1} N	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
N2O CAN	t N2O-N yr^{-1}	2268.5	1874.5	1481.4	1167.3	1041.5	1072.1	862.0	657.9	446.8	421.9	1228.4
N2O UREA	t N2O-N yr^{-1}	78.7	61.6	49.0	39.7	27.2	16.6	0.0	0.0	0.0	0.0	32.2
N2O NH3SO4	t N2O-N yr^{-1}	13.5	11.2	9.6	9.1	9.3	11.3	11.1	10.9	10.4	9.8	10.9

N2O compounds	t N2O-N yr^{-1}	2651.1	2213.3	1885.2	1782.6	1835.1	2232.4	2194.0	2152.8	2046.7	1932.6	2135.7
N2O PU	t N2O-N yr^{-1}	39.5	43.9	75.0	146.5	214.7	339.0	409.6	455.6	484.2	457.2	244.6
N2O PU+DCD	t N2O-N yr^{-1}									12.8	24.1	18.4
Total N2O emissions with protected Urea	**t N2O-N yr^{-1}**	5051.3	4204.6	3500.2	3145.1	3127.9	3671.4	3476.8	3277.2	3000.9	2845.6	3655.1
Reduction in N2O-N PU	**t N2O-N yr^{-1}**	**26.5**	**34.6**	**110.6**	**269.1**	**387.0**	**604.4**	**725.4**	**846.1**	**919.3**	**856.0**	**435.5**
Reduction in N2O with PU+Nit. Inhibitor	**t N2O-N yr^{-1}**									**165.9**	**313.4**	**239.7**
KT CO2e	**kt CO_2-e yr^{-1}**	**11.0**	**14.4**	**46.0**	**112.1**	**161.1**	**251.7**	**302.1**	**352.3**	**382.8**	**356.4**	**181.3**
										69.1	**130.5**	**99.8**
extra CO2 urea (PU)	**kt CO_2-e yr^{-1}**	7.2	8.1	13.8	26.9	39.4	62.1	75.1	83.5	88.8	83.8	44.8
extra CO2 urea (PU+NI)	**kt CO_2-e yr^{-1}**									9.4	17.7	13.5
Net Reduction	**kt CO_2-e yr^{-1}**	**3.8**	**6.3**	**32.3**	**85.2**	**121.8**	**189.6**	**227.0**	**268.8**	**294.0**	**272.6**	**136.5**
Reduction in N2O-N PU+NI (CO2e)	**kt CO_2-e yr^{-1}**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**59.7**	**112.8**	**17.3**

Costs – Pathway 1

		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Tonne Urea replaced	**Low Cost**	6598.7	9159.8	7214.4	9246.0	14461.1	23483.2	29215.3	29042.2	28067.4	26992.0	18348.0
Tonne CAN replaced		3326.4	4726.9	12122.6	19226.2	27944.5	43652.2	53018.7	62220.6	69328.9	88443.3	38401.0
Cost of replacing urea		€857,830	€1,190,779	€937,871	€1,201,980	€1,879,948	€3,052,819	€3,797,983	€3,775,482	€3,648,758	€3,508,960	€2,385,241
Cost of replacing CAN		-€399,168	-€567,227	-€1,454,709	-€2,307,148	-€3,353,335	-€5,238,265	-€6,362,238	-€7,466,477	-€8,319,468	-€10,613,197	-€4,608,123
Total Cost		€458,662	€623,552	-€516,838	-€1,105,168	-€1,473,386	-€2,185,446	-€2,564,255	-€3,690,995	-€4,670,710	-€7,104,237	-€2,222,882
Abatement Cost		€119.89	€109.66	-€15.52	-€19.97	-€18.59	-€17.80	-€17.29	-€20.50	-€22.72	-€26.08	€7.11
Cost of replacing urea	**High Cost**	€1,715,659	€2,381,558	€1,875,741	€2,403,959	€3,759,897	€6,105,638	€7,595,966	€7,550,963	€7,297,516	€7,017,920	€4,770,482
Cost of replacing CAN		-€997,919	-€1,418,067	-€3,636,772	-€5,767,870	-€8,383,337	-€13,095,663	-€15,905,596	-€18,666,192	-€20,798,669	-€26,532,992	-€11,520,308
Total Cost		**€717,740**	**€963,491**	**-€1,761,031**	**-€3,363,911**	**-€4,623,440**	**-€6,990,025**	**-€8,309,630**	**-€11,115,228**	**-€13,501,154**	**-€19,515,072**	**-€6,749,826**
Abatement Cost		**€187.61**	**€169.45**	**-€52.89**	**-€60.79**	**-€58.34**	**-€56.94**	**-€56.03**	**-€61.72**	**-€65.67**	**-€71.64**	**-€12.70**

Pathway 2

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Tonne Urea replaced	6560	6846	6997	8822	13622	22095	27144	26634	25322	23910	15701
Tonne CAN replaced	3307	4141	11757	27793	40058	62653	75257	87270	95737	90398	45452
									12765	**24106**	**18436**
Cost of replacing urea	€852,793	€889,927	€909,624	€1,146,804	€1,770,914	€2,872,412	€3,528,690	€3,462,404	€3,291,895	€3,108,313	€2,183,378
Cost of replacing CAN	-€396,824	-€496,924	-€1,410,897	-€3,335,214	-€4,806,941	-€7,518,371	-€9,030,892	-€10,472,383	-€11,488,457	-€10,847,768	-€5,980,467
Total Cost	€455,969	€393,003	-€501,272	-€2,188,410	-€3,036,026	-€4,645,958	-€5,502,202	-€7,009,979	-€8,196,561	-€7,739,455	-€3,797,089
Abatement Cost	€41.31	€27.30	-€10.89	-€19.53	-€18.84	-€18.46	-€18.21	-€19.90	-€21.41	-€21.71	-€8.03
Cost of replacing urea	€1,705,586	€1,779,853	€1,819,249	€2,293,608	€3,541,829	€5,744,825	€7,057,380	€6,924,808	€6,583,790	€6,216,626	€4,366,755
Cost of replacing CAN	-€992,060	-€1,242,310	-€3,527,242	-€8,338,035	-€12,017,352	-€18,795,927	-€22,577,229	-€26,180,957	-€28,721,142	-€27,119,420	-€14,951,167
Total Cost	**€713,526**	**€537,544**	**-€1,707,993**	**-€6,044,427**	**-€8,475,523**	**-€13,051,102**	**-€15,519,849**	**-€19,256,149**	**-€22,137,351**	**-€20,902,795**	**-€10,584,412**
Abatement Cost	**€64.64**	**€37.35**	**-€37.09**	**-€53.94**	**-€52.60**	**-€51.85**	**-€51.37**	**-€54.65**	**-€57.83**	**-€58.64**	**-€31.60**
Cost of replacing CAN with PU+DCD Low Cost									**€893,547**	**€1,687,431**	**€1,290,489**
Cost of replacing CAN with PU+DCD High Cost									**€1,787,093**	**€3,374,861**	**€2,580,977**
Abatement Cost (Low Cost)									**€14.96**	**€14.96**	**€14.96**
Abatement Cost (High Cost)									**€29.91**	**€29.91**	**€29.91**

Table A1.10b: Overview of Modelling Assumptions Used and Results for high nitrate compound fertilisers replaced with ammonium-based compounds

CONVERT 50% OF COMPOUNDS TO LOW NO3	**Pathway 1**		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Amount of High NO3- compounds	t N yr^{-1}		146,670	152,388	128,482	111,071	106,762	111,320	135,578	134,937	134,138	129,636	124,669	128,695
High NO3- compounds N2O BAU	t N_2O-N yr^{-1}		2,053	2,133	1,799	1,555	1,495	1,558	1,898	1,889	1,878	1,815	1,745	1,802
Uptake	Percentage			0%	10%	15%	20%	25%	30%	35%	40%	45%	50%	27%
N2O compounds WAM		assumption - 40% reduction in EF from 1.4% to 0.84%	2053	2133	1727	1462	1375	1403	1670	1625	1577	1488	1396	1628.2
Reduction in N2O-N	t N_2O-N yr^{-1}		0.0	0.0	71.9	93.3	119.6	155.8	227.8	264.5	300.5	326.7	349.1	173.6
CO2e abatement	**kt CO_2e yr^{-1}**		**0.0**	**0.0**	**30.0**	**38.9**	**49.8**	**64.9**	**94.9**	**110.1**	**125.1**	**136.0**	**145.4**	**72.3**
CONVERT 65% OF COMPOUNDS TO LOW NO3	Pathway 2													
Amount of High NO3- compounds	t N yr^{-1}		146,670	151,493	126,472	107,726	101,861	104,864	127,566	125,370	123,015	116,957	110,434	122,039
High NO3- compounds N2O BAU	t N_2O-N yr^{-1}		2,053	2,121	1,771	1,508	1,426	1,468	1,786	1,755	1,722	1,637	1,546	1,709
Uptake	Percentage		0%	0%	10%	15%	20%	30%	40%	50%	55%	60%	65%	31%
N2O compounds WAM		assumption - 40% reduction in EF from 1.4% to 0.84%	2053	2121	1700	1418	1312	1292	1500	1404	1343	1244	1144	1503
Reduction in N2O-N	t N_2O-N yr^{-1}		0.00	0.00	70.82	90.49	114.08	176.17	285.75	351.04	378.89	392.97	401.98	206
CO2e abatement	**kt CO_2e yr^{-1}**		**0.0**	**0.0**	**29.5**	**37.7**	**47.5**	**73.4**	**119.0**	**146.2**	**157.8**	**163.6**	**167.4**	**85.6**

Total Fertiliser Pathway 1

Abatement (PU+ Compounds)		**3.83**	**34.68**	**72.15**	**105.13**	**144.15**	**217.62**	**258.45**	**305.21**	**341.63**	**417.77**	190.1
Marginal Abatement Cost		**€119.89**	**€17.98**	**-€7.16**	**-€10.51**	**-€10.22**	**-€10.04**	**-€9.92**	**-€12.09**	**-€13.67**	**-€17.00**	**€4.7**
Marginal Abatement Cost		**€187.61**	**€27.78**	**-€24.41**	**-€32.00**	**-€32.07**	**-€32.12**	**-€32.15**	**-€36.42**	**-€39.52**	**-€46.71**	**-€6.0**

Total Fertiliser Pathway 2

Total abatement (PU& compounds&PU+NI)		3.80333	35.83009	69.97683	132.72332	195.13668	308.54905	373.17686	426.57468	517.42811	552.84082	261.60
Abatement Cost (Low Cost)		€119.89	€10.97	-€7.16	-€16.49	-€15.56	-€15.06	-€14.74	-€16.43	-€14.11	-€10.95	€2.03
Abatement Cost (High Cost)		€187.61	€15.00	-€24.41	-€45.54	-€43.43	-€42.30	-€41.59	-€45.14	-€42.78	-€37.81	-€12.04

Table A1.11: Overview of Modelling Assumptions Used and Results for the Inclusion of Lipids into Bovine Diets

	Lipid introduction in the dairy herd		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Population	Dairy cows	Units	1511.9	1554.9	1599.8	1616.6	1608.6	1608.9	1623.7	1643.4	1662.9	1679.3	1691.8	
	Heifers '000s	000 head	330.5	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3	
Enteric Methane EF	Cows	kg CH4 hd^{-1}	122.4	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5	
	Heifers	kg CH4 hd^{-1}	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	
Methane emissions	Cows	t CH_4 yr^{-1}	184980	191484	198290	201674	201988	203338	206544	210407	214280	217809	220859	
	Heifers	t CH_4 yr^{-1}	18151	16298	16843	16746	16754	16934	17171	17406	17604	17754	17863	
Lipids	g/kg in diet per cow		0	0	10	20	30	50	70	100	100	100	100	
	Methane reduction %		0.00%	0.00%	1.25%	2.50%	3.75%	6.25%	8.75%	12.50%	12.50%	12.50%	12.50%	
	uptake dairy Pathway 1		0%	0%	0%	1%	2%	3%	4%	6%	7%	8%	8%	
	Methane reduction	t CH_4 yr^{-1}	0.00	0.00	0.00	54.61	123.04	344.17	783.00	1708.59	2028.98	2208.40	2387.22	876.18
	CO2 equivalent reduction	**kt CO_2e yr^{-1}**	**0.00**	**0.00**	**0.00**	**1.53**	**3.45**	**9.64**	**21.92**	**47.84**	**56.81**	**61.84**	**66.84**	**24.53**
	uptake dairy Pathway 2		0.00%	0.00%	0.00%	1.5%	3.0%	5.0%	8.0%	12.0%	13.0%	14.0%	15.0%	
	Methane reduction (tCH4e yr) per cow	t CH_4 yr^{-1}	0.000	0.000	0.000	82	246	688	1566	3417	3768	4122	4476	1669.64
	CO2 equivalent reduction	**kt CO_2e yr^{-1}**	**0.00**	**0.00**	**0.00**	**2.29**	**6.89**	**19.27**	**43.85**	**95.68**	**105.51**	**115.43**	**125.33**	**46.75**

	Lipid introduction in the dairy herd		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Low cost	COST at 36.12 per head Rapecake	€ yr^{-1}	0	0	0	€694,041	€1,036,833	€1,731,279	€2,797,700	€4,248,455	€5,014,810	€5,425,041	€5,828,648	**€2,677,681**
High cost	COST at 55 per head linseed	€ yr^{-1}	0	0	0	€1,056,818	€1,578,788	€2,636,222	€4,260,064	€6,469,131	€7,636,062	€8,260,722	€8,875,295	**€4,077,310**
Low cost	COST at 36.12 per head Rapecake	€ yr^{-1}	0	0	0	€1,041,062	€2,073,666	€3,462,558	€5,595,400	€8,496,910	€9,313,219	€10,126,744	€10,928,716	**€5,103,827**
High cost	COST at 55 per head linseed	€ yr^{-1}	0	0	0	€1,585,228	€3,157,576	€5,272,444	€8,520,127	€12,938,262	€14,181,258	€15,420,015	€16,641,179	**€7,771,609**
Low cost	**Euro per tCO2e abated Rapecake (Pathway 1)**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€453.94**	**€300.95**	**€179.65**	**€127.61**	**€88.80**	**€88.27**	**€87.73**	**€87.20**	**€141.42**
High cost	**Euro per tCO2e abated linseed (Pathway 1)**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€691.21**	**€458.26**	**€273.56**	**€194.31**	**€135.22**	**€134.41**	**€133.59**	**€132.78**	**€215.33**
Low cost	**Euro per tCO2e abated Rapecake (Pathway 2)**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€453.94**	**€300.95**	**€179.65**	**€127.61**	**€88.80**	**€88.27**	**€87.73**	**€87.20**	**€141.42**
High cost	**Euro per tCO2e abated linseed (Pathway 2)**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€691.21**	**€458.26**	**€273.56**	**€194.31**	**€135.22**	**€134.41**	**€133.59**	**€132.78**	**€215.33**

Table A 1.12: Overview of Modelling Assumptions Used and Results for the inclusion of feed additives (3NOP/halides) in bovine diets

Population	**Pathway 1**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	000 head	1,551.1	1,554.9	1,599.8	1,616.6	1,608.6	1,608.9	1,623.7	1,643.4	1,662.9	1,679.3	1,691.8
Other Cows	000 head	916.9	915.0	892.8	847.8	802.6	764.4	735.1	709.0	682.9	657.7	632.0
Cattle < 1 yrs - male	000 head	1,027.9	1,027.9	1,059.5	1,038.4	1,062.8	1,072.7	1,062.7	1,050.1	1,039.1	1,032.4	1,027.9
Cattle 1 - 2 yrs - male	000 head	864.3	864.3	797.6	781.7	800.0	807.4	799.9	790.4	782.2	777.1	773.7
Cattle > 2 yrs - male	000 head	363.6	363.6	373.4	366.0	374.5	378.0	374.5	370.1	366.2	363.8	362.2
Cattle < 1 yrs - female	000 head	1,118.0	1,118.0	1,070.1	1,049.0	1,080.9	1,093.0	1,078.7	1,060.9	1,043.2	1,036.6	1,026.3
Cattle 1 - 2 yrs - female	000 head	661.8	733.9	640.4	627.7	646.8	654.1	645.5	634.9	624.3	620.3	614.2
Cattle > 2 yrs - female	000 head	248.2	225.9	204.3	200.2	206.3	208.7	205.9	202.5	199.1	197.9	195.9
Bulls	000 head	49.5	49.3	49.5	47.2	44.8	42.3	40.1	38.0	35.8	33.5	31.1
Dairy Heifers	000 head	335.7	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3
Other Heifers	000 head	138.4	136.4	138.1	130.6	124.3	119.6	116.9	114.4	111.5	108.2	104.7
Methane per head												
Dairy Cows	kg CH_4 hd^{-1}	122.4	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5
Other Cows	kg CH_4 hd^{-1}	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3
Cattle < 1 yrs - male	kg CH_4 hd^{-1}	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	29.7
Cattle 1 - 2 yrs - male	kg CH_4 hd^{-1}	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	59.1
Cattle > 2 yrs - male	kg CH_4 hd^{-1}	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.0
Cattle < 1 yrs - female	kg CH_4 hd^{-1}	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	27.7
Cattle 1 - 2 yrs - female	kg CH_4 hd^{-1}	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	47.0
Cattle > 2 yrs - female	kg CH_4 hd^{-1}	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	22.6
Bulls	kg CH_4 hd^{-1}	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	81.5

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Dairy Heifers	kg CH_4 hd^{-1}	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9
Other Heifers	kg CH_4 hd^{-1}	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	53.7
Total Enteric Methane												
Dairy Cows	tCH_4 yr^{-1}	189,785	191,484	198,290	201,674	201,988	203,338	206,544	210,407	214,280	217,809	220,859
Other Cows	tCH_4 yr^{-1}	67,246	67,106	65,479	62,175	58,860	56,063	53,914	51,996	50,083	48,235	46,349
Cattle < 1 yrs - male	tCH_4 yr^{-1}	36,523	36,523	37,647	36,898	37,762	38,114	37,759	37,312	36,921	36,682	30,538
Cattle 1 - 2 yrs - male	tCH_4 yr^{-1}	50,422	50,422	46,528	45,602	46,669	47,105	46,665	46,113	45,630	45,334	45,703
Cattle > 2 yrs - male	tCH_4 yr^{-1}	13,684	13,684	14,053	13,773	14,096	14,227	14,095	13,928	13,782	13,693	13,396
Cattle < 1 yrs - female	tCH_4 yr^{-1}	36,410	36,410	34,851	34,163	35,201	35,597	35,131	34,552	33,975	33,760	28,450
Cattle 1 - 2 yrs - female	tCH_4 yr^{-1}	34,472	38,228	33,356	32,697	33,691	34,069	33,624	33,069	32,517	32,311	28,866
Cattle > 2 yrs - female	tCH_4 yr^{-1}	5,214	4,745	4,292	4,207	4,335	4,384	4,326	4,255	4,184	4,157	4,418
Bulls	tCH_4 yr^{-1}	4,622	4,604	4,627	4,412	4,179	3,949	3,744	3,545	3,342	3,129	2,536
Dairy Heifers	tCH_4 yr^{-1}	18,437	16,298	16,843	16,746	16,754	16,934	17,171	17,406	17,604	17,754	17,863
Other Heifers	tCH_4 yr^{-1}	8,089	7,975	8,074	7,631	7,268	6,994	6,832	6,686	6,517	6,325	5,621
Total	tCH_4 yr^{-1}	464,905	467,479	464,039	459,977	460,802	460,774	459,804	459,269	458,833	459,188	444,599
GRAZING TIME												
Dairy Cows	percentage	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%	65.11%
Other Cows	percentage	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%	59.44%
Cattle < 1 yrs - male	percentage	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%
Cattle 1 - 2 yrs - male	percentage	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%
Cattle > 2 yrs - male	percentage	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%	59.73%
Cattle < 1 yrs - female	percentage	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%	60.00%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cattle 1 - 2 yrs - female	percentage	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%
Cattle > 2 yrs - female	percentage	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%	59.45%
Bulls	percentage	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%	57.53%
Dairy Heifers	percentage	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%
Other Heifers	percentage	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%	59.18%
Grazing emissions												
Dairy Cows	$tCH_4\ yr^{-1}$	123,569	124,675	129,106	131,310	131,514	132,393	134,480	136,995	139,517	141,815	143,801
Other Cows	$tCH_4\ yr^{-1}$	39,973	39,890	38,922	36,958	34,988	33,326	32,048	30,908	29,771	28,672	27,551
Cattle < 1 yrs - male	$tCH_4\ yr^{-1}$	21,914	21,914	22,588	22,139	22,657	22,869	22,655	22,387	22,152	22,009	18,323
Cattle 1 - 2 yrs - male	$tCH_4\ yr^{-1}$	30,115	30,115	27,789	27,236	27,874	28,134	27,871	27,542	27,253	27,076	27,297
Cattle > 2 yrs - male	$tCH_4\ yr^{-1}$	8,173	8,173	8,393	8,226	8,419	8,497	8,418	8,319	8,231	8,178	8,001
Cattle < 1 yrs - female	$tCH_4\ yr^{-1}$	21,846	21,846	20,911	20,498	21,121	21,358	21,079	20,731	20,385	20,256	17,070
Cattle 1 - 2 yrs - female	$tCH_4\ yr^{-1}$	20,400	22,623	19,739	19,349	19,937	20,162	19,898	19,570	19,243	19,121	17,082
Cattle > 2 yrs - female	$tCH_4\ yr^{-1}$	3,100	2,821	2,551	2,501	2,577	2,606	2,572	2,530	2,487	2,472	2,627
Bulls	$tCH_4\ yr^{-1}$	2,659	2,649	2,662	2,538	2,405	2,272	2,154	2,040	1,923	1,800	1,459
Dairy Heifers	$tCH_4\ yr^{-1}$	10,911	9,645	9,967	9,910	9,914	10,021	10,162	10,300	10,417	10,506	10,571
Other Heifers	$tCH_4\ yr^{-1}$	4,787	4,719	4,778	4,516	4,301	4,139	4,043	3,957	3,857	3,743	3,326
	$tCH_4\ yr^{-1}$											
3NOP Efficacy during Grazing	Percentage	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Uptake												

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Dairy Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	5.00%	20.00%	30.00%	40.00%
Other Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle < 1 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle 1 - 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle > 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle < 1 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle 1 - 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle > 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Bulls	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Dairy Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	5.00%	20.00%	30.00%	40.00%
Other Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Methane Reduction												
Dairy Cows	**tCH_4 yr^{-1}**	-	-	-	-	-	-	94.14	479.48	1,953.24	2,978.12	4,026.43
Dairy Heifers	**tCH_4 yr^{-1}**	-	-	-	-	-	-	7.11	36.05	145.84	220.63	295.99
Total reduction CH4	**tCH_4 yr^{-1}**	-	-	-	-	-	-	101.25	515.54	2,099.09	3,198.75	4,322.42
Total reduction ktCO2e	**tCO_2e yr^{-1}**	**-**	**-**	**-**	**-**	**-**	**-**	**2.83**	**14.43**	**58.77**	**89.57**	**121.03**
Housing Period												
Dairy Cows	Percentage	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%	34.89%
Other Cows	Percentage	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%	40.56%
Cattle < 1 yrs - male	Percentage	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%
Cattle 1 - 2 yrs - male	Percentage	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cattle > 2 yrs - male	Percentage	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%	40.27%
Cattle < 1 yrs - female	Percentage	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%
Cattle 1 - 2 yrs - female	Percentage	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%
Cattle > 2 yrs - female	Percentage	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%	40.55%
Bulls	Percentage	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%	42.47%
Dairy Heifers	Percentage	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%
Other Heifers	Percentage	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%	40.82%
3NOP EFFICACY												
Beef	Percentage	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Dairy autumn calvers	Percentage	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Dairy spring calvers	Percentage	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%
% dairy calving												
% Spring calvers	Percentage	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
% Autumn calvers	Percentage	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Uptake												
Spring Dairy Cows	Percentage	0%	0%	0%	0%	0%	2%	2%	5%	10%	15%	20%
Autumn	Percentage	0%	0%	0%	0%	0%	2%	5%	10%	30%	50%	60%
Other Cows	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cattle < 1 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	1%	7%	14%	19%	10%
Cattle 1 - 2 yrs - male	Percentage	0%	0%	0%	0%	0%	1%	1%	7%	14%	19%	28%
Cattle > 2 yrs - male	Percentage	0%	0%	0%	0%	0%	1%	1%	7%	14%	19%	35%
Cattle < 1 yrs - female	Percentage	0%	0%	0%	0%	0%	1%	1%	7%	14%	19%	21%
Cattle 1 - 2 yrs - female	Percentage	0%	0%	0%	0%	0%	1%	1%	7%	14%	19%	10%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cattle > 2 yrs - female	Percentage	0%	0%	0%	0%	0%	1%	1%	7%	14%	19%	28%
Bulls	Percentage	0%	0%	0%	0%	0%	1%	3%	6%	9%	12%	35%
Dairy Heifers	Percentage	0%	0%	0%	0%	0%	3%	5%	7%	15%	23%	28%
Other Heifers	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Methane reduction												
Dairy Cows (Spring)	tCH_4 yr^{-1}	0	0	0	0	0	127.7	173.0	440.5	897.2	1367.9	1849.4
Dairy Cows (Autumn)	tCH_4 yr^{-1}	0	0	0	0	0	61.9	209.4	426.7	1303.6	2208.4	2687.2
Other Cows	tCH_4 yr^{-1}	0	0	0	0	0	0	0	0	0	0	0
Cattle < 1 yrs - male	tCH_4 yr^{-1}	0	0	0	0	0	0.0	45.3	313.4	620.3	836.3	366.5
Cattle 1 - 2 yrs - male	tCH_4 yr^{-1}	0	0	0	0	0	56.9	56.4	390.0	771.8	1040.7	1546.1
Cattle > 2 yrs - male	tCH_4 yr^{-1}	0	0	0	0	0	17.2	17.0	117.8	233.1	314.3	566.5
Cattle < 1 yrs - female	tCH_4 yr^{-1}	0	0	0	0	0	42.7	42.2	290.2	570.8	769.7	716.9
Cattle 1 - 2 yrs - female	tCH_4 yr^{-1}	0	0	0	0	0	41.7	41.2	283.5	557.5	751.8	353.5
Cattle > 2 yrs - female	tCH_4 yr^{-1}	0	0	0	0	0	5.3	5.3	36.2	71.2	96.1	150.5
Bulls	tCH_4 yr^{-1}	0	0	0	0	0	5.0	14.3	27.1	38.3	47.8	113.1
Dairy Heifers	tCH_4 yr^{-1}	0	0	0	0	0	62.2	105.1	149.2	323.4	500.1	612.5
Other Heifers	tCH_4 yr^{-1}	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total Methane	**tCH_4 yr^{-1}**	0	0	0	0	0	420.7	709.1	2474.6	5387.2	7933.2	8962.2
Total ktCO2E yr-1	**tCO_2e yr^{-1}**	0	0	0	0	0	11.78	19.86	69.29	150.84	222.13	250.94
Total reduction		-	-	-	-	-	**11.78**	**22.69**	**83.72**	**209.62**	**311.70**	**371.97**
											Mean	**168.58**
Population	**Pathway 2**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	000 head	1,551.1	1,554.9	1,599.8	1,616.6	1,608.6	1,608.9	1,623.7	1,643.4	1,662.9	1,679.3	1,691.8

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Other Cows	000 head	916.9	915.0	892.8	847.8	802.6	764.4	735.1	709.0	682.9	657.7	632.0
Cattle < 1 yrs - male	000 head	1,027.9	1,027.9	1,059.5	1,038.4	1,062.8	1,072.7	1,062.7	1,050.1	1,039.1	1,032.4	1,027.9
Cattle 1 - 2 yrs - male	000 head	864.3	864.3	797.6	781.7	800.0	807.4	799.9	790.4	782.2	777.1	773.7
Cattle > 2 yrs - male	000 head	363.6	363.6	373.4	366.0	374.5	378.0	374.5	370.1	366.2	363.8	362.2
Cattle < 1 yrs - female	000 head	1,118.0	1,118.0	1,070.1	1,049.0	1,080.9	1,093.0	1,078.7	1,060.9	1,043.2	1,036.6	1,026.3
Cattle 1 - 2 yrs - female	000 head	661.8	733.9	640.4	627.7	646.8	654.1	645.5	634.9	624.3	620.3	614.2
Cattle > 2 yrs - female	000 head	248.2	225.9	204.3	200.2	206.3	208.7	205.9	202.5	199.1	197.9	195.9
Bulls	000 head	49.5	49.3	49.5	47.2	44.8	42.3	40.1	38.0	35.8	33.5	31.1
Dairy Heifers	000 head	335.7	296.8	306.7	304.9	305.1	308.3	312.7	316.9	320.5	323.3	325.3
Other Heifers	000 head	138.4	136.4	138.1	130.6	124.3	119.6	116.9	114.4	111.5	108.2	104.7
Methane per head												
Dairy Cows	kg CH4 hd-1	122.4	123.1	123.9	124.8	125.6	126.4	127.2	128.0	128.9	129.7	130.5
Other Cows	kg CH4 hd-1	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3
Cattle < 1 yrs - male	kg CH4 hd-1	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	29.7
Cattle 1 - 2 yrs - male	kg CH4 hd-1	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	59.1
Cattle > 2 yrs - male	kg CH4 hd-1	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.0
Cattle < 1 yrs - female	kg CH4 hd-1	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	27.7
Cattle 1 - 2 yrs - female	kg CH4 hd-1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	47.0
Cattle > 2 yrs - female	kg CH4 hd-1	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	22.6
Bulls	kg CH4 hd-1	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	81.5
Dairy Heifers	kg CH4 hd-1	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	54.9	50.2
Other Heifers	kg CH4 hd-1	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	53.7

Population	**Pathway 1**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Total Enteric Methane												
Dairy Cows	tCH4 yr-1	189,785.5	191,484.4	198,289.7	201,674.2	201,988.4	203,337.9	206,543.6	210,406.6	214,280.0	217,809.0	220,859.1
Other Cows	tCH4 yr-1	67,246.1	67,106.1	65,478.6	62,174.9	58,860.0	56,063.5	53,914.4	51,995.9	50,083.2	48,235.3	46,348.7
Cattle < 1 yrs - male	tCH4 yr-1	36,523.2	36,523.2	37,647.4	36,897.9	37,761.7	38,114.2	37,758.5	37,312.1	36,920.8	36,681.7	30,537.9
Cattle 1 - 2 yrs - male	tCH4 yr-1	50,421.7	50,421.7	46,527.8	45,601.6	46,669.0	47,104.7	46,665.1	46,113.4	45,629.8	45,334.3	45,703.1
Cattle > 2 yrs - male	tCH4 yr-1	13,684.0	13,684.0	14,053.0	13,773.3	14,095.7	14,227.3	14,094.5	13,927.9	13,781.8	13,692.5	13,395.8
Cattle < 1 yrs - female	tCH4 yr-1	36,409.9	36,409.9	34,851.1	34,162.6	35,201.1	35,597.1	35,131.4	34,551.9	33,974.6	33,759.7	28,450.2
Cattle 1 - 2 yrs - female	tCH4 yr-1	34,471.6	38,227.9	33,355.5	32,696.6	33,690.5	34,069.5	33,623.8	33,069.2	32,516.6	32,311.0	28,865.7
Cattle > 2 yrs - female	tCH4 yr-1	5,214.3	4,744.8	4,291.7	4,206.9	4,334.8	4,383.5	4,326.2	4,254.8	4,183.7	4,157.3	4,418.1
Bulls	tCH4 yr-1	4,622.2	4,604.3	4,626.8	4,412.0	4,179.5	3,949.0	3,743.5	3,545.5	3,341.9	3,128.6	2,536.0
Dairy Heifers	tCH4 yr-1	18,437.1	16,297.7	16,842.6	16,746.2	16,753.5	16,933.6	17,171.4	17,405.6	17,603.5	17,753.8	16,315.9
Other Heifers	tCH4 yr-1	8,089.5	7,974.7	8,074.5	7,630.7	7,267.5	6,993.5	6,831.6	6,685.9	6,517.3	6,325.3	5,621.0
Total	tCH4 yr-1	464,905.0	467,478.7	464,038.7	459,976.9	460,801.7	460,773.7	459,804.0	459,268.5	458,833.2	459,188.3	443,051.6
GRAZING TIME												
Dairy Cows	percentage	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%	69.00%
Other Cows	percentage	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%	56.00%
Cattle < 1 yrs - male	percentage	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%	34.00%
Cattle 1 - 2 yrs - male	percentage	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%	33.00%
Cattle > 2 yrs - male	percentage	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%	51.00%
Cattle < 1 yrs - female	percentage	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%	53.00%
Cattle 1 - 2 yrs - female	percentage	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%	87.00%
Cattle > 2 yrs - female	percentage	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Bulls	percentage	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%	45.00%
Dairy Heifers	percentage	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%	61.00%
Other Heifers	percentage	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%	58.00%
Grazing emissions												
Dairy Cows	tCH4 yr-1	130,952.0	132,124.3	136,819.9	139,155.2	139,372.0	140,303.2	142,515.1	145,180.5	147,853.2	150,288.2	152,392.8
Other Cows	tCH4 yr-1	37,657.8	37,579.4	36,668.0	34,818.0	32,961.6	31,395.6	30,192.1	29,117.7	28,046.6	27,011.8	25,955.3
Cattle < 1 yrs - male	tCH4 yr-1	12,417.9	12,417.9	12,800.1	12,545.3	12,839.0	12,958.8	12,837.9	12,686.1	12,553.1	12,471.8	10,382.9
Cattle 1 - 2 yrs - male	tCH4 yr-1	16,639.2	16,639.2	15,354.2	15,048.5	15,400.8	15,544.5	15,399.5	15,217.4	15,057.8	14,960.3	15,082.0
Cattle > 2 yrs - male	tCH4 yr-1	6,978.8	6,978.8	7,167.0	7,024.4	7,188.8	7,255.9	7,188.2	7,103.2	7,028.7	6,983.2	6,831.9
Cattle < 1 yrs - female	tCH4 yr-1	19,297.2	19,297.2	18,471.1	18,106.2	18,656.6	18,866.4	18,619.6	18,312.5	18,006.5	17,892.6	15,078.6
Cattle 1 - 2 yrs - female	tCH4 yr-1	29,990.3	33,258.3	29,019.3	28,446.0	29,310.8	29,640.4	29,252.7	28,770.2	28,289.4	28,110.5	25,113.2
Cattle > 2 yrs - female	tCH4 yr-1	5,214.3	4,744.8	4,291.7	4,206.9	4,334.8	4,383.5	4,326.2	4,254.8	4,183.7	4,157.3	4,418.1
Bulls	tCH4 yr-1	2,080.0	2,071.9	2,082.1	1,985.4	1,880.8	1,777.1	1,684.6	1,595.5	1,503.9	1,407.9	1,141.2
Dairy Heifers	tCH4 yr-1	11,246.6	9,941.6	10,274.0	10,215.2	10,219.6	10,329.5	10,474.6	10,617.4	10,738.2	10,829.8	9,952.7
Other Heifers	tCH4 yr-1	4,691.9	4,625.3	4,683.2	4,425.8	4,215.2	4,056.2	3,962.3	3,877.8	3,780.0	3,668.6	3,260.2
3NOP Efficacy during Grazing	Percentage	7%	7%	7%	7%	7%	7%	7%	7%	7%	20%	20%
Uptake												
Dairy Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	5.00%	20.00%	40.00%	50.00%
Other Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle < 1 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Cattle 1 - 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle > 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle < 1 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle 1 - 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle > 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Bulls	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Dairy Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Methane Reduction												
Dairy Cows	tCH4 yr-1	-	-	-	-	-	-	99.76	508.13	2,069.94	12,023.05	15,239.28
Other Cows	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle < 1 yrs - male	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle 1 - 2 yrs - male	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle > 2 yrs - male	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle < 1 yrs - female	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle 1 - 2 yrs - female	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Cattle > 2 yrs - female	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Bulls	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Dairy Heifers	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Other Heifers	tCH4 yr-1	-	-	-	-	-	-	-	-	-	-	-
Total reduction CH_4	tCH4 yr-1	-	-	-	-	-	-	99.76	508.13	2,069.94	12,023.05	15,239.28

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Total reduction $ktCO_2e$	tCO2e yr-1	-	-	-	-	-	-	2.79	14.23	57.96	336.65	426.70
Housing Period												
Dairy Cows	Percentage											
Other Cows	Percentage	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%	31.00%
Cattle < 1 yrs - male	Percentage	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%	44.00%
Cattle 1 - 2 yrs - male	Percentage	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%	66.00%
Cattle > 2 yrs - male	Percentage	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%	67.00%
Cattle < 1 yrs - female	Percentage	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%	49.00%
Cattle 1 - 2 yrs - female	Percentage	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%	47.00%
Cattle > 2 yrs - female	Percentage	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%	13.00%
Bulls	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Dairy Heifers	Percentage	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%	55.00%
Other Heifers	Percentage	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%	39.00%
3NOP EFFICACY		42.00%	42.00%	42.00%	42.00%	42.00%	42.00%	42.00%	42.00%	42.00%	42.00%	42.00%
Beef	Percentage											
Dairy autumn calvers	Percentage	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Dairy spring calvers	Percentage	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
% calving		15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%
% Spring calvers	Percentage	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
% Autumn calvers	Percentage	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Uptake	% dairy calving											
Spring Dairy Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.50%	5.00%	10.00%	20.00%	30.00%	40.00%

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Autumn	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.50%	5.00%	10.00%	30.00%	50.00%	70.00%
Other Cows	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle < 1 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle 1 - 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	1.00%	10.00%	20.00%	35.00%	45.00%
Cattle > 2 yrs - male	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	1.00%	10.00%	20.00%	35.00%	45.00%
Cattle < 1 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Cattle 1 - 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	1.00%	10.00%	20.00%	35.00%	45.00%
Cattle > 2 yrs - female	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	1.00%	10.00%	20.00%	35.00%	45.00%
Bulls	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	3.00%	6.00%	9.00%	12.00%	35.00%
Dairy Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	3.00%	5.00%	7.00%	15.00%	23.00%	28.00%
Other Heifers	Percentage	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3NOP Mitigation												
Dairy Cows (Spring)	$tCH_4\ yr^{-1}$	0	0	0	0	0	113.46	384.17	782.71	1594.24	2430.75	3286.38
Dairy Cows (Autumn)	$tCH_4\ yr^{-1}$	0	0	0	0	0	67.10	227.20	462.89	1414.25	2395.90	3401.23
Other Cows	$tCH_4\ yr^{-1}$	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Cattle < 1 yrs - male	$tCH_4\ yr^{-1}$	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Cattle 1 - 2 yrs - male	$tCH_4\ yr^{-1}$	0	0	0	0	0	94.68	93.80	926.88	1834.32	3189.27	4133.84
Cattle > 2 yrs - male	$tCH_4\ yr^{-1}$	0	0	0	0	0	20.91	20.72	204.74	405.19	704.48	886.13
Cattle < 1 yrs - female	$tCH_4\ yr^{-1}$	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Cattle 1 - 2 yrs - female	$tCH_4\ yr^{-1}$	0	0	0	0	0	13.29	13.11	128.97	253.63	441.04	506.59
Cattle > 2 yrs - female	$tCH_4\ yr^{-1}$	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Bulls	$tCH_4\ yr^{-1}$	0	0	0	0	0	6.52	18.53	35.10	49.63	61.95	146.46
Dairy Heifers	$tCH_4\ yr^{-1}$	0	0	0	0	0	59.44	100.45	142.55	308.94	477.76	534.51

Population	Pathway 1	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Other Heifers	tCH_4 yr^{-1}	0	0	0	0	0	0	0	0	0	0	0
Total	tCH_4 yr^{-1}	0	0	0	0	0	375.40	857.98	2683.85	5860.19	9701.14	12895.15
Total ktCO2E yr-1	tCO_2e yr^{-1}	0	0	0	0	0	10.5	24.0	75.1	164.1	271.6	361.1
Total reduction	tCO_2e yr^{-1}	-	-	-	-	-	10.51	26.82	89.38	222.04	608.28	787.76
											Mean	290.80

Costs

Pathway 1

Low													
Costs		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Dairy grazing	**€**	-	-	-	-	-	-	€423,305	€2,142,183	€8,670,121	€13,133,993	€17,642,551	
Dairy cows spring	**€**	-	-	-	-	-	€271,842	€365,792	€925,568	€1,873,039	€2,837,386	€3,811,387	
Dairy cows autumn	**€**	-	-	-	-	-	€67,960	€228,620	€462,784	€1,404,779	€2,364,488	€2,858,540	
Beef	**€**	-	-	-	-	-	€542,815	€801,403	€4,198,912	€7,994,553	€10,705,504	€14,014,189	
Euro total	**€**	**-**	**-**	**-**	**-**	**-**	**€882,617**	**€1,819,120**	**€7,729,447**	**€19,942,492**	**€29,041,372**	**€38,326,667**	**€16,290,286**
Abatement Cost	**€ t^{-1} CO2**	**-**	**-**	**-**	**-**	**-**	**€74.93**	**€80.17**	**€92.32**	**€95.14**	**€93.17**	**€103.04**	**€89.79**
High													
Costs		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Dairy grazing	**€**	-	-	-	-	-	-	678,831	3,435,308	13,903,821	21,062,301	28,292,439	
Dairy cows spring	**€**	-	-	-	-	-	€362,640	€487,972	€1,234,719	€2,498,658	€3,785,109	€5,084,438	
Dairy cows autumn	**€**	-	-	-	-	-	€90,660	€304,982	€617,360	€1,873,993	€3,154,258	€3,813,329	
Beef	**€**	-	-	-	-	-	€603,128	€1,108,113	€4,509,942	€9,398,614	€13,292,196	€16,932,647	
Euro total	**€**	**-**	**-**	**-**	**-**	**-**	**€1,056,428**	**€2,579,898**	**€9,797,329**	**€27,675,086**	**€41,293,863**	**€54,122,853**	**€22,754,243**
Abatement Cost	**€ t^{-1} CO2**	**-**	**-**	**-**	**-**	**-**	**€89.69**	**€113.70**	**€117.02**	**€132.03**	**€132.48**	**€145.50**	**€121.74**

Pathway 2

			2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Low Cost	Dairy grazing	**€**	-	-	-	-	-	449,828	2,276,409	9,213,376	18,609,262	23,435,002	€8,997,313
	Dairy cows spring	**€**	-	-	-	-	€240,304	€808,387	€1,636,375	€3,311,474	€5,016,410	€6,738,412	€2,958,560
	Dairy cows autumn	**€**	-	-	-	-	€60,076	€202,097	€409,094	€1,241,803	€2,090,171	€2,948,055	€1,158,549
	Beef	**€**	-	-	-	-	€15,148	€26,844	€1,028,773	€3,946,615	€11,521,352	€20,753,335	€6,215,345
	Euro total	**€**	-	-	-	-	€315,528	€1,487,155	€5,350,651	€17,713,268	€37,237,194	€53,874,805	€19,329,767
	Abatement Cost	**€ $t^{-1}CO2$**	-	-	-	-	**€30.02**	**€55.46**	**€59.87**	**€79.77**	**€61.22**	**€68.39**	**€59**
High Cost	Dairy grazing	**€**					€0	€678,831	€3,435,308	€13,903,821	€28,083,067	€35,365,549	€13,577,763
	Dairy cows spring	**€**					€362,640	€1,219,929	€2,469,439	€4,997,316	€7,570,218	€10,168,877	€4,464,736
	Dairy cows autumn	**€**					€90,660	€304,982	€617,360	€1,873,993	€3,154,258	€4,448,884	€1,748,356
	Beef	**€**					€31,113	€55,133	€2,112,954	€8,105,790	€23,663,228	€42,624,414	€12,765,439
	Euro total	**€**					€484,413	€2,258,876	€8,635,060	€28,880,920	€62,470,771	€92,607,724	€32,556,294
	Abatement Cost	**€ $t^{-1}CO2$**					**€46.09**	**€84.23**	**€96.62**	**€130.07**	**€102.70**	**€117.56**	**€96.21**

Table A1.13: Overview of Modelling Assumptions Used and Results for Low Emission Slurry Spreading

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
N applied to field (from crude protein sheet)		134617.1	136501.4	133503.7	131434.1	130806.1	130561.2	130548.2	131132.9	131798.6	132458.8	133086.3
TAN applied to field		73964.78	75005.35	73370.36	72240.67	71900.63	71771.95	71770.93	72097.36	72468.23	72836	73185.76
Timing of slurry spreading - proportion of total												
Spring	Percentage	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%
Summer	Percentage	36%	36%	36%	36%	36%	36%	36%	36%	36%	36%	36%
Autumn	Percentage	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%
Winter	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Landspreading emission factor (proportion of TAN)												
Summer	Percentage	48%	48%	48%	48%	48%	48%	48%	48%	48%	48%	48%
Autum, winter, spring	Percentage	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%
Emission Factors												
Trailing Hose - Summer EF	kg NH_3-N kg^{-1} N	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339	0.339
Trailing Hose - Other EF	kg NH_3-N kg^{-1} N	0.183	0.183	0.183	0.183	0.183	0.183	0.183	0.183	0.183	0.183	0.183
Trailing Shoe - Summer EF	kg NH_3-N kg^{-1} N	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0.194	0.194
Trailing Shoe - Other EF	kg NH_3-N kg^{-1} N	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104
Percentage Slurry sourced from derogation farms	Percentage	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%
Uptake Trailing Hose - Derogation	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Uptake Trailing Hose - Non Derogation	Percentage	5%	10%	20%	28%	28%	28%	30%	33%	33%	33%	33%
Uptake Trailing Shoe - Derogation	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Uptake Trailing Shoe - Non Derogation	Percentage	5%	10%	20%	28%	28%	28%	30%	33%	33%	33%	33%
Percentage slurry allocated to Trailing Hose	Percentage	17%	20%	28%	33%	33%	33%	35%	37%	37%	37%	37%
Percentage slurry allocated to Trailing Shoe	Percentage	17%	20%	28%	33%	33%	33%	35%	37%	37%	37%	37%
Ammonia loss BAU (Splashplate)	tNH_3-N yr^{-1}	22341	25708	25138	24748	24629	24582	24578	24687	24811	24934	25050
Ammonia loss BAU (Trailing Hose)	tNH_3-N yr^{-1}	3731	5244	6988	8253	8214	8198	8652	9147	9192	9238	9281
Ammonia loss BAU (Trailing Shoe)	tNH_3-N yr^{-1}	3731	5244	6988	8253	8214	8198	8652	9147	9192	9238	9281

Ammonia loss (More LESS)	tNH_3-N yr^{-1}	21547	20988	18849	17320	17237	17204	16792	16455	16538	16620	16697
Ammonia loss with increased Trailing Hose	tNH_3-N yr^{-1}	2964	3671	4892	5777	5750	5739	6056	6403	6435	6467	6497
Ammonia loss with increased Trailing Shoe	tNH_3-N yr^{-1}	1694	2098	2795	3301	3286	3279	3461	3659	3677	3695	3712
Ammonia loss from remainder splashplate	tNH_3-N yr^{-1}	16888	15219	11161	8241	8202	8186	7275	6394	6426	6458	6488
Ammonia abatement (Trailing Hose)	tNH_3-N yr^{-1}	767	1573	2097	2476	2464	2459	2595	2744	2758	2771	2784
Indirect N2O-N (Trailing Hose)	tN_2O-N yr^{-1}	7.7	15.7	21.0	24.8	24.6	24.6	26.0	27.4	27.6	27.7	27.8
Fertiliser savings due to lower ammonia	tN yr^{-1}	11.5	23.6	31.4	37.1	37.0	36.9	38.9	41.2	41.4	41.6	41.8
Total Trailing Hose Abatement	**tCO_2e yr^{-1}**	**8.0**	**16.4**	**21.8**	**25.8**	**25.7**	**25.6**	**27.0**	**28.6**	**28.7**	**28.9**	**29.0**
Ammonia abatement (Trailing Shoe)	tNH_3-N yr^{-1}	2037	3147	4193	4952	4928	4919	5191	5488	5515	5543	5569
Indirect N2O-N (Trailing Shoe)	tN_2O-N yr^{-1}	20.4	31.5	41.9	49.5	49.3	49.2	51.9	54.9	55.2	55.4	55.7
Fertiliser savings due to lower ammonia	tN yr^{-1}	30.6	47.2	62.9	74.3	73.9	73.8	77.9	82.3	82.7	83.1	83.5
Total Trailing Shoe Abatement	**tCO_2e yr^{-1}**	**21.2**	**32.8**	**43.7**	**51.6**	**51.3**	**51.2**	**54.0**	**57.1**	**57.4**	**57.7**	**58.0**
Total Abatement	**tCO_2e yr^{-1}**	**29.2**	**49.1**	**65.5**	**77.3**	**77.0**	**76.8**	**81.1**	**85.7**	**86.1**	**86.6**	**87.0**

Costs

Low Cost		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Trailing Hose	No of units	644	800	1068	1263	1257	1254	1324	1400	1407	1414	1421	1261
Gross cost	€	€6,553,887	€8,133,452	€10,865,139	€12,845,594	€12,784,224	€12,760,287	€13,470,488	€14,245,467	€14,317,788	€14,389,508	14457678.28	€12,826,963
Euro N saving	€	€933,688	€1,916,289	€2,553,589	€3,015,805	€3,001,334	€2,995,594	€3,161,274	€3,342,134	€3,358,908	€3,375,540	3391339.608	€3,011,181
Net cost	€	€5,620,199	€6,217,164	€8,311,551	€9,829,789	€9,782,890	€9,764,693	€10,309,214	€10,903,333	€10,958,880	€11,013,968	11066338.67	€9,815,782
cost per tCO2	€/tCO2e	€626.25	€337.54	€338.63	€339.11	€339.12	€339.13	€339.28	€339.42	€339.44	€339.47	€339.49	€339.06
Trailing Shoe	No of units	644	800	1068	1263	1257	1254	1324	1400	1407	1414	1421	1261
Gross cost	€	€10,807,208	€13,411,875	€17,916,363	€21,182,087	€21,080,889	€21,041,418	€22,212,523	€23,490,445	€23,609,700	€23,727,965	23840376.57	€21,151,364
Euro N saving	€	€2,481,081	€56,639	€75,476	€89,137	€88,709	€88,540	€93,437	€98,782	€99,278	€99,770	100236.6387	€89,000

Net cost	€	€8,326,127	€13,355,236	€17,840,888	€21,092,950	€20,992,180	€20,952,878	€22,119,086	€23,391,663	€23,510,422	€23,628,195	23740139.93	€21,062,364
cost per tCO2	€/tCO2e	€349.14	€362.54	€363.44	€363.83	€363.84	€363.85	€363.97	€364.09	€364.11	€364.13	€364.15	€363.79
High cost		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Trailing Hose	No of units	644	800	1068	1263	1257	1254	1324	1400	1407	1414	1421	1261
Gross cost	€	€7,794,047	€9,672,506	€12,921,096	€15,276,303	€15,203,320	€15,174,854	€16,019,442	€16,941,067	€17,027,072	€17,112,364	€17,193,434	€15,254,146
Euro N saving	€	€2,022,991	€4,151,959	€5,532,775	€6,534,245	€6,502,890	€6,490,453	€6,849,427	€7,241,290	€7,277,633	€7,313,669	7347902.484	€6,524,224
Net cost	€	€5,771,056	€5,520,547	€7,388,321	€8,742,058	€8,700,429	€8,684,400	€9,170,015	€9,699,777	€9,749,439	€9,798,695	9845531.275	€8,729,921
cost per tCO2	€/tCO2e	€643	€300	€301	€302	€302	€302	€302	€302	€302	€302	€302.04	€301.53
Trailing Shoe	No of units	644	800	1068	1263	1257	1254	1324	1400	1407	1414	1421	1261
Gross cost	€	€12,047,368	€14,950,928	€19,972,320	€23,612,796	€23,499,985	€23,455,985	€24,761,477	€26,186,045	€26,318,985	€26,450,821	€26,576,132	€23,578,547
Euro N saving	€	€5,375,676	€8,303,918	€11,065,550	€13,068,490	€13,005,781	€12,980,907	€13,698,854	€14,482,580	€14,555,266	€14,627,338	14695804.97	€13,048,449
Net cost	€	€6,671,692	€6,647,010	€8,906,770	€10,544,306	€10,494,204	€10,475,078	€11,062,623	€11,703,465	€11,763,719	€11,823,483	11880327.08	€10,530,098
cost per tCO2	€/tCO2e	€280	€180	€181	€182	€182	€182	€182	€182	€182	€182	€182.23	€181.84

Table A1.14: Overview of Modelling Assumptions Used and Results for Manure Acidification and Use of Manure Amendments

BAU Scenario												
Population	**Units**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	000 head	1,551.1	1,580.8	1,589.5	1,597.5	1,615.0	1,635.7	1,656.4	1,676.6	1,695.6	1,713.4	1,730.2
Other Cows	000 head	916.9	899.5	863.7	832.7	804.9	777.8	750.6	722.9	694.6	666.0	637.4
Cattle < 1 yrs - male	000 head	1,027.9	1,040.1	1,024.3	1,036.3	1,036.1	1,026.8	1,024.0	1,020.8	1,017.2	1,013.4	1,009.2
Cattle 1 - 2 yrs - male	000 head	864.3	782.9	771.0	780.0	779.9	772.9	770.8	768.4	765.7	762.8	759.7
Cattle > 2 yrs - male	000 head	363.6	366.5	361.0	365.2	365.1	361.9	360.9	359.7	358.5	357.1	355.7
Cattle < 1 yrs - female	000 head	1,118.0	1,026.5	1,010.9	1,025.1	1,023.3	1,010.0	1,004.8	999.1	993.2	987.2	983.7
Cattle 1 - 2 yrs - male	000 head	661.8	614.2	604.9	613.4	612.3	604.4	601.3	597.9	594.4	590.8	588.7
Cattle > 2 yrs - female	000 head	248.2	195.9	193.0	195.7	195.3	192.8	191.8	190.7	189.6	188.5	187.8
Bulls	000 head	49.5	50.1	48.3	46.6	45.0	43.2	41.4	39.5	37.5	35.4	32.7
Dairy Heifers	000 head	335.7	337.6	339.4	343.2	347.8	352.3	356.8	361.0	364.9	368.5	367.1
Other Heifers	000 head	138.4	141.4	133.8	129.5	126.2	123.1	119.9	116.6	113.2	109.7	106.1
Gilts in Pig	000 head	20.5	20.4	20.5	20.6	20.7	20.8	20.9	21.0	21.0	21.1	21.2
Gilts not yet Served	000 head	16.3	16.4	16.5	16.6	16.7	16.7	16.8	16.9	16.9	17.0	17.1
Sows in Pig	000 head	79.2	82.9	83.4	83.9	84.3	84.7	85.1	85.4	85.7	86.1	86.5
Other Sows for Breeding	000 head	29.0	28.4	28.6	28.7	28.8	29.0	29.1	29.2	29.3	29.4	29.5

Boars	000 head	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Pigs 20 Kg +	000 head	1,071.4	1,087.7	1,085.4	1,088.2	1,093.5	1,100.7	1,109.0	1,117.9	1,126.9	1,136.2	1,145.7
Pigs Under 20 Kg	000 head	438.2	445.2	444.6	445.8	448.0	450.8	454.1	457.5	461.1	464.7	468.3
Layer	000 head	3,752.6	4,252.0	4,239.0	4,268.7	4,313.6	4,372.6	4,444.0	4,525.8	4,609.5	4,692.6	4,774.7
Broiler	000 head	13,706.2	14,173.9	14,130.7	14,229.7	14,379.5	14,576.0	14,814.1	15,086.8	15,365.9	15,642.7	15,916.6
Turkey	000 head	1,374.7	1,629.1	1,624.1	1,635.5	1,652.7	1,675.3	1,702.7	1,734.0	1,766.1	1,797.9	1,829.4
Ducks	000 head	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1
Geese	000 head	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
EF's for Manure Management		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	kg CH_4 hd^{-1}	17.23	17.68	18.02	18.12	18.21	18.41	18.64	18.88	19.11	19.33	19.53
Other Cows	kg CH_4 hd^{-1}	7.25	6.98	6.84	6.57	6.33	6.12	5.92	5.71	5.50	5.28	5.07
Cattle < 1 yrs - male	kg CH_4 hd^{-1}	5.02	5.10	5.16	5.08	5.14	5.14	5.09	5.08	5.06	5.04	5.02
Cattle 1 - 2 yrs - male	kg CH_4 hd^{-1}	4.82	5.27	4.77	4.70	4.76	4.75	4.71	4.70	4.68	4.67	4.65
Cattle > 2 yrs - male	kg CH_4 hd^{-1}	0.61	0.54	0.55	0.54	0.54	0.54	0.54	0.54	0.54	0.53	0.53
Cattle < 1 yrs - female	kg CH_4 hd^{-1}	5.15	5.21	4.78	4.71	4.78	4.77	4.71	4.68	4.66	4.63	4.60
Cattle 1 - 2 yrs - male	kg CH_4 hd^{-1}	3.42	3.52	3.27	3.22	3.26	3.26	3.22	3.20	3.18	3.16	3.14
Cattle > 2 yrs - female	kg CH_4 hd^{-1}	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Bulls	kg CH_4 hd^{-1}	0.51	0.50	0.51	0.49	0.47	0.45	0.44	0.42	0.40	0.38	0.36
Dairy Heifers	kg CH_4 hd^{-1}	1.48	1.50	1.51	1.52	1.53	1.56	1.58	1.60	1.61	1.63	1.65
Other Heifers	kg CH_4 hd^{-1}	0.80	0.71	0.72	0.68	0.66	0.65	0.63	0.61	0.60	0.58	0.56
Gilts in Pig	kg CH_4 hd^{-1}	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
Gilts not yet Served	kg CH_4 hd^{-1}	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82

Sows in Pig	kg CH_4 hd^{-1}	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
Other Sows for Breeding	kg CH_4 hd^{-1}	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95
Boars	kg CH_4 hd^{-1}	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88
Pigs 20 Kg +	kg CH_4 hd^{-1}	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53
Pigs Under 20 Kg	kg CH_4 hd^{-1}	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80
Layer	kg CH_4 hd^{-1}	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Broiler	kg CH_4 hd^{-1}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Turkey	kg CH_4 hd^{-1}	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Ducks	kg CH_4 hd^{-1}	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Geese	kg CH_4 hd^{-1}	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Emissions from Manure Management - Gg of CH_4		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	ktCH_4 yr^{-1}	26.728	27.946	28.638	28.941	29.404	30.108	30.880	31.652	32.401	33.113	33.788
Other Cows(CH4 Gg/Yr)	ktCH_4 yr^{-1}	6.647	6.274	5.910	5.471	5.098	4.762	4.441	4.128	3.820	3.519	3.229
Under1yr - male (CH4 Gg/Yr)	ktCH_4 yr^{-1}	5.164	5.301	5.282	5.263	5.324	5.275	5.214	5.183	5.148	5.111	5.071
Oneto2yrs - male (CH4 Gg/Yr)	ktCH_4 yr^{-1}	4.162	4.125	3.680	3.667	3.709	3.675	3.632	3.611	3.587	3.561	3.533
Over2yrs - male (CH4 Gg/Yr)	ktCH_4 yr^{-1}	0.222	0.198	0.197	0.196	0.198	0.197	0.194	0.193	0.192	0.190	0.189
Under1yr - female (CH4 Gg/Yr)	ktCH_4 yr^{-1}	5.752	5.349	4.836	4.830	4.889	4.817	4.730	4.679	4.625	4.570	4.526
Oneto2yrs - female (CH4 Gg/Yr)	ktCH_4 yr^{-1}	2.264	2.163	1.977	1.975	1.999	1.969	1.934	1.913	1.891	1.868	1.850
Over2yrs - female (CH4 Gg/Yr)	ktCH_4 yr^{-1}	0.015	0.012	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Bulls(CH4 Gg/Yr)	ktCH_4 yr^{-1}	0.025	0.025	0.024	0.023	0.021	0.020	0.018	0.017	0.015	0.013	0.012

Dairy Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.496	0.507	0.512	0.521	0.534	0.548	0.562	0.576	0.589	0.601	0.605
Other Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.111	0.100	0.097	0.089	0.084	0.079	0.075	0.072	0.068	0.063	0.059
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.175	0.174	0.175	0.176	0.177	0.177	0.178	0.179	0.179	0.180	0.181
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.127	0.128	0.129	0.130	0.130	0.131	0.131	0.132	0.132	0.133	0.133
Sows in Pig	$ktCH_4\ yr^{-1}$	0.675	0.707	0.711	0.715	0.719	0.722	0.725	0.728	0.731	0.734	0.737
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.665	0.653	0.656	0.659	0.662	0.665	0.667	0.670	0.672	0.675	0.677
Boars	$ktCH_4\ yr^{-1}$	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.848	4.922	4.912	4.924	4.949	4.981	5.018	5.059	5.100	5.142	5.185
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.296	4.365	4.359	4.371	4.393	4.420	4.452	4.486	4.521	4.556	4.592
Layers	$ktCH_4\ yr^{-1}$	3.475	3.938	3.926	3.953	3.995	4.049	4.116	4.191	4.269	4.346	4.422
Broilers	$ktCH_4\ yr^{-1}$	0.181	0.187	0.187	0.188	0.190	0.192	0.196	0.199	0.203	0.207	0.210
Turkeys	$ktCH_4\ yr^{-1}$	0.127	0.151	0.150	0.151	0.153	0.155	0.157	0.160	0.163	0.166	0.169
Ducks	$ktCH_4\ yr^{-1}$	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Geese	$ktCH_4\ yr^{-1}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Total BAU CH_4 from Manure Management	$ktCH_4\ yr^{-1}$	**66.3**	**67.4**	**66.5**	**66.4**	**66.8**	**67.1**	**67.5**	**68.0**	**68.4**	**68.9**	**69.3**
CO2e emissions	**$ktCO_2e\ yr^{-1}$**	**1856.1**	**1886.0**	**1862.1**	**1858.8**	**1869.6**	**1878.4**	**1889.0**	**1903.1**	**1916.6**	**1929.0**	**1940.7**
Uptake rate		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Other Cows	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	4%	6%	8%
Cattle < 1 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	0%	20%	20%	6%	8%
Cattle 1 - 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Cattle > 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Cattle < 1 yrs - female	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Cattle 1 - 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Cattle > 2 yrs - female	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Bulls	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Dairy Heifers	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%

Other Heifers	Percentage	0%	0%	0%	0%	0%	0%	0%	2%	2%	6%	8%
Gilts in Pig	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Gilts not yet Served	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Sows in Pig	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Other Sows for Breeding	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Boars	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Pigs 20 Kg +	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Pigs Under 20 Kg	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Layer	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Broiler	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Turkey	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Ducks	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
Geese	Percentage	0%	0%	0%	0%	0%	3%	6%	9%	10%	11%	11%
1,000 (head/1,000 head) / 1,000,000 g/Gg		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Pathway 1												
Emissions from Manure Management - Gg of CH_4		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	26.7	27.9	28.6	28.9	29.4	29.4	29.6	29.8	30.1	30.6	31.2
Other Cows(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	6.6	6.3	5.9	5.5	5.1	4.8	4.4	4.1	3.7	3.4	3.0
Under1yr - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.2	5.3	5.3	5.3	5.3	5.3	5.2	4.5	4.4	4.9	4.8
Oneto2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	4.2	4.1	3.7	3.7	3.7	3.7	3.6	3.6	3.5	3.4	3.3
Over2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Under1yr - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.8	5.3	4.8	4.8	4.9	4.8	4.7	4.6	4.6	4.4	4.3
Oneto2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	2.3	2.2	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.7
Over2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulls(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Other Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sows in Pig	$ktCH_4\ yr^{-1}$	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Boars	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.8	4.9	4.9	4.9	4.9	4.9	4.8	4.8	4.7	4.8	4.8
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.3	4.4	4.4	4.4	4.4	4.3	4.3	4.2	4.2	4.2	4.2
Layers	$ktCH_4\ yr^{-1}$	3.5	3.9	3.9	4.0	4.0	4.0	4.0	4.0	4.1	4.1	4.2
Broilers	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Turkeys	$ktCH_4\ yr^{-1}$	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ducks	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Geese	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total CH_4 from Manure Management	$ktCH_4\ yr^{-1}$	**66.3**	**67.4**	**66.5**	**66.4**	**66.8**	**66.0**	**65.5**	**64.3**	**64.2**	**64.5**	**64.5**
CO_2e emissions	**$ktCO_2e\ yr^{-1}$**	**1856.1**	**1886.0**	**1862.1**	**1858.8**	**1869.6**	**1848.5**	**1834.1**	**1799.7**	**1796.4**	**1805.0**	**1804.7**
CO_2e Abatement	**$ktCO_2e\ yr^{-1}$**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**29.9**	**54.9**	**103.5**	**120.1**	**123.9**	**136.0**
Storage												
Ammonia Bovines	$t\ NH_3\text{-}N\ yr^{-1}$	5348.4	5423.6	5305.4	5223.7	5199.1	5189.8	5189.7	5213.3	5240.1	5266.7	5292.0
Ammonia Pigs	$t\ NH_3\text{-}N\ yr^{-1}$	1311.8	1320.1	1305.5	1295.3	1287.4	1280.8	1274.9	1269.3	1263.7	1258.1	1252.5
Ammonia Poultry	$t\ NH_3\text{-}N\ yr^{-1}$	802.7	822.0	834.3	844.4	852.8	858.3	862.4	865.8	869.4	872.5	875.8

Total	t NH_3-N yr^{-1}	7462.8	7565.7	7445.2	7363.4	7339.3	7328.9	7327.0	7348.4	7373.2	7397.4	7420.3
Reduction Level	Percentage	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**
Uptake												
Bovines	Percentage	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.63%**	**1.11%**	**4.59%**	**5.07%**	**6.85%**	**8.55%**
Pigs	Percentage	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**3.30%**	**6.10%**	**8.53%**	**10.00%**	**10.67%**	**11.05%**
Poultry	Percentage	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**3.30%**	**6.10%**	**8.53%**	**10.00%**	**10.67%**	**11.05%**
Emissions post acidification												
Treated ammonia Bovines	t NH_3-N yr^{-1}	**5348**	**5424**	**5305**	**5224**	**5199**	**5167**	**5149**	**5046**	**5054**	**5014**	**4975**
Treated ammonia Pigs	t NH_3-N yr^{-1}	**1312**	**1320**	**1305**	**1295**	**1287**	**1251**	**1220**	**1193**	**1175**	**1164**	**1156**
Treated ammonia Poultry	t NH_3-N yr^{-1}	**803**	**822**	**834**	**844**	**853**	**839**	**826**	**814**	**809**	**807**	**808**
Total	t NH_3-N yr^{-1}	**7463**	**7566**	**7445**	**7363**	**7339**	**7257**	**7195**	**7053**	**7038**	**6986**	**6939**
Reduction (ammonia-N)	t NH_3-N yr^{-1}	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**72.1**	**131.6**	**295.0**	**335.2**	**411.7**	**481.5**
Reduction (Indirect N2O)	ktCO_2e yr^{-1}	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.30**	**0.55**	**1.23**	**1.40**	**0.00**	**0.00**
Total reduction	**ktCO_2e yr^{-1}**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**30.23**	**55.45**	**104.68**	**121.54**	**123.92**	**136.02**
											Mean	**63.54**

Uptake Pathway 2	Units	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Other Cows(CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	0%	0%	1%	5%	8%	9%	10%
Under1yr - male (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Oneto2yrs - male (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Over2yrs - male (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Under1yr - female (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Oneto2yrs - female (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Over2yrs - female (CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Bulls(CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	1%	3%	5%	9%	12%	13%	15%
Dairy Heifers(CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Other Heifers(CH4 Gg/Yr)	Percentage	0%	0%	0%	0%	0%	0%	1%	5%	8%	9%	10%
Gilts in Pig	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Gilts not yet served	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Sows in Pig	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Other Sows for Breeding	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Boars	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Pigs >20kg	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Pigs < 20kg	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Layers	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Broilers	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Turkeys	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Ducks	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
Geese	Percentage	0%	0%	0%	0%	2%	5%	9%	13%	16%	18%	20%
1,000 (head/1,000 head) / 1,000,000 g/Gg		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Emissions from Manure Management - Gg of CH_4		**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	26.728	27.946	28.638	28.941	29.404	30.108	30.880	31.652	32.401	33.113	33.788
Other Cows(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	6.647	6.274	5.910	5.471	5.098	4.762	4.441	4.128	3.820	3.519	3.229
Under1yr - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.164	5.301	5.282	5.263	5.324	5.275	5.214	5.183	5.148	5.111	5.071
Oneto2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	4.162	4.125	3.680	3.667	3.709	3.675	3.632	3.611	3.587	3.561	3.533
Over2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.222	0.198	0.197	0.196	0.198	0.197	0.194	0.193	0.192	0.190	0.189
Under1yr - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.752	5.349	4.836	4.830	4.889	4.817	4.730	4.679	4.625	4.570	4.526
Oneto2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	2.264	2.163	1.977	1.975	1.999	1.969	1.934	1.913	1.891	1.868	1.850
Over2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.015	0.012	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Bulls(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.025	0.025	0.024	0.023	0.021	0.020	0.018	0.017	0.015	0.013	0.012
Dairy Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.496	0.507	0.512	0.521	0.534	0.548	0.562	0.576	0.589	0.601	0.605
Other Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.111	0.100	0.097	0.089	0.084	0.079	0.075	0.072	0.068	0.063	0.059
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.175	0.174	0.175	0.176	0.177	0.177	0.178	0.179	0.179	0.180	0.181
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.127	0.128	0.129	0.130	0.130	0.131	0.131	0.132	0.132	0.133	0.133
Sows in Pig	$ktCH_4\ yr^{-1}$	0.675	0.707	0.711	0.715	0.719	0.722	0.725	0.728	0.731	0.734	0.737
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.665	0.653	0.656	0.659	0.662	0.665	0.667	0.670	0.672	0.675	0.677
Boars	$ktCH_4\ yr^{-1}$	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.848	4.922	4.912	4.924	4.949	4.981	5.018	5.059	5.100	5.142	5.185
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.296	4.365	4.359	4.371	4.393	4.420	4.452	4.486	4.521	4.556	4.592
Layers	$ktCH_4\ yr^{-1}$	3.475	3.938	3.926	3.953	3.995	4.049	4.116	4.191	4.269	4.346	4.422
Broilers	$ktCH_4\ yr^{-1}$	0.181	0.187	0.187	0.188	0.190	0.192	0.196	0.199	0.203	0.207	0.210
Turkeys	$ktCH_4\ yr^{-1}$	0.127	0.151	0.150	0.151	0.153	0.155	0.157	0.160	0.163	0.166	0.169
Ducks	$ktCH_4\ yr^{-1}$	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Geese	$ktCH_4\ yr^{-1}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Total CH_4 from Manure Management	$ktCH_4\ yr^{-1}$	**66.3**	**67.4**	**66.5**	**66.4**	**66.8**	**67.1**	**67.5**	**68.0**	**68.4**	**68.9**	**69.3**
kT CO_2e		**1856.1**	**1886.0**	**1862.1**	**1858.8**	**1869.5**	**1878.4**	**1889.0**	**1903.1**	**1916.6**	**1928.9**	**1940.7**
Emissions from Manure Management - Gg of CH_4	Units	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	26.7	27.9	28.6	28.9	29.0	29.1	28.9	28.8	28.8	28.9	29.1
Other Cows(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	6.6	6.3	5.9	5.5	5.1	4.8	4.4	4.0	3.6	3.3	3.0
Under1yr - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.2	5.3	5.3	5.3	5.3	5.2	5.0	4.9	4.7	4.6	4.5
Oneto2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	4.2	4.1	3.7	3.7	3.7	3.6	3.5	3.4	3.3	3.2	3.2
Over2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Under1yr - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.8	5.3	4.8	4.8	4.9	4.7	4.6	4.4	4.2	4.2	4.1
Oneto2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	2.3	2.2	2.0	2.0	2.0	1.9	1.9	1.8	1.7	1.7	1.7
Over2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulls(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sows in Pig	$ktCH_4\ yr^{-1}$	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Boars	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.8	4.9	4.9	4.9	4.9	4.8	4.7	4.6	4.5	4.5	4.5
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.3	4.4	4.4	4.4	4.3	4.3	4.2	4.1	4.0	4.0	3.9
Layers	$ktCH_4\ yr^{-1}$	3.5	3.9	3.9	4.0	4.0	3.9	3.9	3.9	3.9	4.0	4.0
Broilers	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Turkeys	$ktCH_4\ yr^{-1}$	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2

Ducks	ktCH_4 yr^{-1}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Geese	ktCH_4 yr^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total CH4 from Manure Management (CH4 Gg/Yr)	ktCH_4 yr^{-1}	**66.3**	**67.4**	**66.5**	**66.4**	**66.0**	**65.2**	**64.0**	**62.6**	**61.6**	**61.1**	**60.6**
CO2e emissions	**ktCO_2e yr^{-1}**	**1856.1**	**1886.0**	**1862.1**	**1858.8**	**1849.1**	**1826.5**	**1791.8**	**1752.2**	**1724.4**	**1712.1**	**1695.9**
CO2e Abatement	**ktCO_2e yr^{-1}**	**0.000**	**0.000**	**0.000**	**0.000**	**20.48**	**51.91**	**97.28**	**150.96**	**192.17**	**216.83**	**244.85**
Ammonia Bovines	t NH_3-N yr^{-1}	5348.4	5423.6	5305.4	5223.7	5199.1	5189.8	5189.7	5213.3	5240.1	5266.7	5292.0
Ammonia Pigs	t NH_3-N yr^{-1}	1311.8	1320.1	1305.5	1295.3	1287.4	1280.8	1274.9	1269.3	1263.7	1258.1	1252.5
Ammonia Poultry	t NH_3-N yr^{-1}	802.7	822.0	834.3	844.4	852.8	858.3	862.4	865.8	869.4	872.5	875.8
Total	t NH_3-N yr^{-1}	7462.8	7565.7	7445.2	7363.4	7339.3	7328.9	7327.0	7348.4	7373.2	7397.4	7420.3
Reduction 75%		75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
Bovines	Percentage	0.0	0.000	0.000	0.000	0.010	0.025	0.050	0.090	0.120	0.132	0.150
Pigs	Percentage	0.000	0.000	0.000	0.000	0.020	0.050	0.090	0.130	0.160	0.180	0.200
Poultry	Percentage	0.000	0.000	0.000	0.000	0.020	0.050	0.090	0.130	0.160	0.180	0.200
Treated ammonia Bovines	t NH_3-N yr^{-1}	5348.4	5423.6	5305.4	5223.7	5162.7	5099.0	5008.1	4884.9	4800.0	4780.76	4736.36
Treated ammonia Pigs	t NH_3-N yr^{-1}	1311.8	1320.1	1305.5	1295.3	1269.4	1236.0	1194.6	1153.8	1122.2	1099.61	1077.18
Treated ammonia Poultry	t NH_3-N yr^{-1}	802.7	822.0	834.3	844.4	840.9	828.3	808.0	787.0	772.0	762.6	753.2
Total	**t NH_3-N yr^{-1}**	**7462.8**	**7565.7**	**7445.2**	**7363.4**	**7273.0**	**7163.2**	**7010.7**	**6825.7**	**6694.2**	**6642.9**	**6566.7**
Reduction (ammonia)	**t NH_3-N yr^{-1}**	**0.0**	**0.0**	**0.0**	**0.0**	**66.4**	**165.7**	**316.3**	**522.7**	**679.1**	**754.4**	**853.6**
Reduction (Indirect N_2O)	**ktCO_2e yr^{-1}**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0003**	**0.0007**	**0.0013**	**0.0022**	**0.0028**	**0.0031**	**0.0012**
Total reduction	**ktCO_2e yr^{-1}**	**0.00**	**0.00**	**0.00**	**0.00**	**30.48**	**51.91**	**97.28**	**150.97**	**192.17**	**216.83**	**244.86**
											Mean	**108.28**

Costs – Pathway 1

High Cost		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
No farms	**Number**	0	0	0	0	637	1132	2925	5044	6780	8450	2774
N saving	**€ yr^{-1}**	0.000	0.000	0.000	0.000	€191,849	€350,024	€784,827	€891,531	€1,095,247	€1,280,846	€510,480
Cost of amendments	**€ yr^{-1}**	€0	€0	€0	€0	€2,269,045	€4,031,660	€10,419,990	€17,967,044	€24,150,968	€30,098,088	€9,881,866
Net Total Cost	**€ yr^{-1}**	***€0***	***€0***	***€0***	***€0***	***€2,077,196***	***€3,681,636***	***€9,635,164***	***€17,075,513***	***€23,055,721***	***€28,817,242***	**€9,371,386**
Abatement Cost	**€ t^{-1} CO_2e**	**€0.00**	**€0.00**	**€0.00**	**€0.00**	**€69.40**	**€67.06**	**€93.14**	**€142.13**	**€186.05**	**€211.86**	**€128.27**
Low Cost												
No farms	**Number**	0	0	0	0	637	1132	2925	5044	6780	8450	2774
N saving	**€ yr^{-1}**	0	0	0	0	€86,548	€157,906	€354,057	€402,194	€494,096	€577,825	€230,292
Cost of amendments	**€ yr^{-1}**	0	0	0	0	€2,000,225	€3,554,018	€9,185,505	€15,838,438	€21,289,736	€26,532,284	€8,711,134
Net Total Cost	**€ yr^{-1}**	***€0***	***€0***	***€0***	***€0***	***€1,913,677***	***€3,396,112***	***€8,831,448***	***€15,436,244***	***€20,795,639***	***€25,954,459***	**€8,480,842**
Abatement Cost	**€ t^{-1} CO_2e**	***€0***	***€0***	***€0***	***€0***	**€63.94**	**€61.86**	**€85.37**	**€128.48**	**€167.81**	**€190.81**	**€77.59**

Costs Pathway 2

High Cost		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
No farms	**Number**	0	0	0	371	928	2470	6412	9368	10539	11710	5971
N saving	**€ yr^{-1}**	€0	€0	€0	€176,509	€440,738	€841,327	€1,390,470	€1,806,350	€2,006,801	€2,270,648	€1,276,120
Cost of amendments	**€ yr^{-1}**	€0	€0	€0	€1,321,502	€3,303,755	€8,796,359	€22,837,763	€33,368,816	€37,539,918	€41,711,020	€21,268,448
Net Total Cost	**€ yr^{-1}**	***€0***	***€0***	***€0***	***€1,144,993***	***€2,863,017***	***€7,955,032***	***€21,447,293***	***€31,562,466***	***€35,533,117***	***€39,440,372***	**€19,992,327**
Abatement Cost	**€ t^{-1} CO_2e**	**€0.00**	**€0.00**	**€0.00**	**€55.91**	**€55.15**	**€81.77**	**€142.07**	**€164.24**	**€163.87**	**€161.08**	**€117.73**
Low Cost												
No farms	**Number**	0	0	0	371	928	2470	6412	9368	10539	11710	5971
N saving	**€ yr^{-1}**	€0	€0	€0	€79,628	€198,829	€379,546	€627,280	€814,895	€905,324	€1,024,352	€575,693
Cost of amendments	**€ yr^{-1}**	0	0	0	1164940	€2,912,350	€7,754,230	€20,132,110	€29,415,520	€33,092,460	€36,769,400	€18,748,716
Net Total Cost	**€ yr^{-1}**	***€0***	***€0***	***€0***	***€1,085,312***	***€2,713,521***	***€7,374,684***	***€19,504,830***	***€28,600,625***	***€32,187,136***	***€35,745,048***	**€18,173,022**
Abatement Cost	**€ t^{-1} CO_2e**	***€0***	***€0***	***€0***	***€53.00***	***€52.27***	***€75.81***	***€129.20***	***€148.83***	***€148.44***	***€145.98***	**€107.65**

Table A1.15: Overview of Modelling Assumptions Used and Results for Manure Aeration

Scenario	**BAU**													
Population	**Units**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	000 head	1,425.0	1,465.3	1,551.1	1,580.8	1,589.5	1,597.5	1,615.0	1,635.7	1,656.4	1,676.6	1,695.6	1,713.4	1,730.2
Other Cows	000 head	1,015.1	978.3	916.9	899.5	863.7	832.7	804.9	777.8	750.6	722.9	694.6	666.0	637.4
Cattle < 1 yrs - male	000 head	998.1	939.5	1,027.9	1,040.1	1,024.3	1,036.3	1,036.1	1,026.8	1,024.0	1,020.8	1,017.2	1,013.4	1,009.2
Cattle 1 - 2 yrs - male	000 head	881.6	837.5	864.3	782.9	771.0	780.0	779.9	772.9	770.8	768.4	765.7	762.8	759.7
Cattle > 2 yrs - male	000 head	410.6	402.7	363.6	366.5	361.0	365.2	365.1	361.9	360.9	359.7	358.5	357.1	355.7
Cattle < 1 yrs - female	000 head	1,080.3	1,068.4	1,118.0	1,026.5	1,010.9	1,025.1	1,023.3	1,010.0	1,004.8	999.1	993.2	987.2	983.7
Cattle 1 - 2 yrs - male	000 head	708.1	681.7	661.8	614.2	604.9	613.4	612.3	604.4	601.3	597.9	594.4	590.8	588.7
Cattle > 2 yrs - female	000 head	237.9	254.0	248.2	195.9	193.0	195.7	195.3	192.8	191.8	190.7	189.6	188.5	187.8
Bulls	000 head	54.8	53.5	49.5	50.1	48.3	46.6	45.0	43.2	41.4	39.5	37.5	35.4	32.7
Dairy Heifers	000 head	302.7	311.4	335.7	337.6	339.4	343.2	347.8	352.3	356.8	361.0	364.9	368.5	367.1
Other Heifers	000 head	146.5	147.7	138.4	141.4	133.8	129.5	126.2	123.1	119.9	116.6	113.2	109.7	106.1
Gilts in Pig	000 head	19.6	19.4	20.5	20.4	20.5	20.6	20.7	20.8	20.9	21.0	21.0	21.1	21.2
Gilts not yet Served	000 head	15.1	17.3	16.3	16.4	16.5	16.6	16.7	16.7	16.8	16.9	16.9	17.0	17.1
Sows in Pig	000 head	80.2	79.0	79.2	82.9	83.4	83.9	84.3	84.7	85.1	85.4	85.7	86.1	86.5
Other Sows for Breeding	000 head	29.7	27.6	29.0	28.4	28.6	28.7	28.8	29.0	29.1	29.2	29.3	29.4	29.5
Boars	000 head	1.3	1.1	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Pigs 20 Kg +	000 head	1,006.9	1,018.8	1,071.4	1,087.7	1,085.4	1,088.2	1,093.5	1,100.7	1,109.0	1,117.9	1,126.9	1,136.2	1,145.7

Pigs Under 20 Kg	000 head	444.4	451.8	438.2	445.2	444.6	445.8	448.0	450.8	454.1	457.5	461.1	464.7	468.3
Layer	000 head	3,601.8	3,651.5	3,752.6	4,252.0	4,239.0	4,268.7	4,313.6	4,372.6	4,444.0	4,525.8	4,609.5	4,692.6	4,774.7
Broiler	000 head	12,006.7	12,832.0	13,706.2	14,173.9	14,130.7	14,229.7	14,379.5	14,576.0	14,814.1	15,086.8	15,365.9	15,642.7	15,916.6
Turkey	000 head	1,380.0	1,300.0	1,374.7	1,629.1	1,624.1	1,635.5	1,652.7	1,675.3	1,702.7	1,734.0	1,766.1	1,797.9	1,829.4
Ducks	000 head	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1	317.1
Geese	000 head	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
EF's for Manure Management		**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	kg CH_4 hd^{-1}	15.91	16.56	17.23	17.68	18.02	18.12	18.21	18.41	18.64	18.88	19.11	19.33	19.53
Other Cows	kg CH_4 hd^{-1}	7.59	7.34	7.25	6.98	6.84	6.57	6.33	6.12	5.92	5.71	5.50	5.28	5.07
Cattle < 1 yrs - male	kg CH_4 hd^{-1}	5.46	4.66	5.02	5.10	5.16	5.08	5.14	5.14	5.09	5.08	5.06	5.04	5.02
Cattle 1 - 2 yrs - male	kg CH_4 hd^{-1}	5.59	5.11	4.82	5.27	4.77	4.70	4.76	4.75	4.71	4.70	4.68	4.67	4.65
Cattle > 2 yrs - male	kg CH_4 hd^{-1}	0.55	0.60	0.61	0.54	0.55	0.54	0.54	0.54	0.54	0.54	0.54	0.53	0.53
Cattle < 1 yrs - female	kg CH_4 hd^{-1}	5.57	4.98	5.15	5.21	4.78	4.71	4.78	4.77	4.71	4.68	4.66	4.63	4.60
Cattle 1 - 2 yrs - male	kg CH_4 hd^{-1}	3.88	3.63	3.42	3.52	3.27	3.22	3.26	3.26	3.22	3.20	3.18	3.16	3.14
Cattle > 2 yrs - female	kg CH_4 hd^{-1}	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Bulls	kg CH_4 hd^{-1}	0.62	0.54	0.51	0.50	0.51	0.49	0.47	0.45	0.44	0.42	0.40	0.38	0.36
Dairy Heifers	kg CH_4 hd^{-1}	1.51	1.39	1.48	1.50	1.51	1.52	1.53	1.56	1.58	1.60	1.61	1.63	1.65
Other Heifers	kg CH_4 hd^{-1}	0.82	0.76	0.80	0.71	0.72	0.68	0.66	0.65	0.63	0.61	0.60	0.58	0.56
Gilts in Pig	kg CH_4 hd^{-1}	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
Gilts not yet Served	kg CH_4 hd^{-1}	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82	7.82
Sows in Pig	kg CH_4 hd^{-1}	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
Other Sows for Breeding	kg CH_4 hd^{-1}	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95	22.95
Boars	kg CH_4 hd^{-1}	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88
Pigs 20 Kg +	kg CH_4 hd^{-1}	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53
Pigs Under 20 Kg	kg CH_4 hd^{-1}	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80

Layer	kg CH_4 hd^{-1}	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Broiler	kg CH_4 hd^{-1}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Turkey	kg CH_4 hd^{-1}	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Ducks	kg CH_4 hd^{-1}	0.46	0.43	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Geese	kg CH_4 hd^{-1}	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Aeration - 40% reduction	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**	**40%**
Uptake		**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Other Cows	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.040	0.080	0.130	0.150
Cattle < 1 yrs - male	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Cattle 1 - 2 yrs - male	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Cattle > 2 yrs - male	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Cattle < 1 yrs - female	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Cattle 1 - 2 yrs - male	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Cattle > 2 yrs - female	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Bulls	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.040	0.080	0.100	0.145	0.180	0.210
Dairy Heifers	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Other Heifers	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.081	0.130	0.150
Gilts in Pig	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Gilts not yet Served	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Sows in Pig	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Other Sows for Breeding	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Boars	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Pigs 20 Kg +	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Pigs Under 20 Kg	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Layer	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Broiler	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Turkey	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
Ducks	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250

Geese	Percentage	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.100	0.150	0.200	0.230	0.250	0.250
1,000 (head/1,000 head) / 1,000,000 g/Gg		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Emissions from Manure Management - No Aeration		**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle	$ktCH_4\ yr^{-1}$	22.673	24.263	26.728	27.946	28.638	28.941	29.404	30.108	30.880	31.652	32.401	33.113	33.788
Other Cows	$ktCH_4\ yr^{-1}$	7.703	7.183	6.647	6.274	5.910	5.471	5.098	4.762	4.441	4.128	3.820	3.519	3.229
Under1yr - male	$ktCH_4\ yr^{-1}$	5.450	4.377	5.164	5.301	5.282	5.263	5.324	5.275	5.214	5.183	5.148	5.111	5.071
Oneto2yrs - male	$ktCH_4\ yr^{-1}$	4.925	4.276	4.162	4.125	3.680	3.667	3.709	3.675	3.632	3.611	3.587	3.561	3.533
Over2yrs - male	$ktCH_4\ yr^{-1}$	0.225	0.241	0.222	0.198	0.197	0.196	0.198	0.197	0.194	0.193	0.192	0.190	0.189
Under1yr - female	$ktCH_4\ yr^{-1}$	6.015	5.320	5.752	5.349	4.836	4.830	4.889	4.817	4.730	4.679	4.625	4.570	4.526
Oneto2yrs - female	$ktCH_4\ yr^{-1}$	2.748	2.473	2.264	2.163	1.977	1.975	1.999	1.969	1.934	1.913	1.891	1.868	1.850
Over2yrs - female	$ktCH_4\ yr^{-1}$	0.014	0.016	0.015	0.012	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Bulls	$ktCH_4\ yr^{-1}$	0.034	0.029	0.025	0.025	0.024	0.023	0.021	0.020	0.018	0.017	0.015	0.013	0.012
Dairy Heifers	$ktCH_4\ yr^{-1}$	0.456	0.434	0.496	0.507	0.512	0.521	0.534	0.548	0.562	0.576	0.589	0.601	0.605
Other Heifers	$ktCH_4\ yr^{-1}$	0.121	0.112	0.111	0.100	0.097	0.089	0.084	0.079	0.075	0.072	0.068	0.063	0.059
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.167	0.165	0.175	0.174	0.175	0.176	0.177	0.177	0.178	0.179	0.179	0.180	0.181
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.118	0.135	0.127	0.128	0.129	0.130	0.130	0.131	0.131	0.132	0.132	0.133	0.133
Sows in Pig	$ktCH_4\ yr^{-1}$	0.684	0.674	0.675	0.707	0.711	0.715	0.719	0.722	0.725	0.728	0.731	0.734	0.737
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.681	0.632	0.665	0.653	0.656	0.659	0.662	0.665	0.667	0.670	0.672	0.675	0.677
Boars	$ktCH_4\ yr^{-1}$	0.011	0.009	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.556	4.610	4.848	4.922	4.912	4.924	4.949	4.981	5.018	5.059	5.100	5.142	5.185
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.357	4.430	4.296	4.365	4.359	4.371	4.393	4.420	4.452	4.486	4.521	4.556	4.592
Layers	$ktCH_4\ yr^{-1}$	3.336	3.382	3.475	3.938	3.926	3.953	3.995	4.049	4.116	4.191	4.269	4.346	4.422
Broilers	$ktCH_4\ yr^{-1}$	0.159	0.169	0.181	0.187	0.187	0.188	0.190	0.192	0.196	0.199	0.203	0.207	0.210
Turkeys	$ktCH_4\ yr^{-1}$	0.128	0.120	0.127	0.151	0.150	0.151	0.153	0.155	0.157	0.160	0.163	0.166	0.169
Ducks	$ktCH_4\ yr^{-1}$	0.146	0.135	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Geese	$ktCH_4\ yr^{-1}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Total CH_4 from Manure Management	$ktCH_4\ yr^{-1}$	64.7	63.2	66.3	67.4	66.5	66.4	66.8	67.1	67.5	68.0	68.4	68.9	69.3
CO_2 equivalents	$ktCO_2e\ yr^{-1}$	1811.8	1769.2	1856.1	1886.0	1862.1	1858.8	1869.6	1878.4	1889.0	1903.1	1916.6	1929.0	1940.7
Emissions from Manure Management - Aeration		**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	22.7	24.3	26.7	27.9	28.6	28.9	28.8	28.9	29.0	29.1	29.4	29.8	30.4
Other Cows(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	7.7	7.2	6.6	6.3	5.9	5.5	5.1	4.8	4.4	4.1	3.7	3.3	3.0
Under1yr - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	5.4	4.4	5.2	5.3	5.3	5.3	5.3	5.2	5.0	5.0	4.8	4.7	4.6
Oneto2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	4.9	4.3	4.2	4.1	3.7	3.7	3.7	3.6	3.5	3.5	3.4	3.3	3.2
Over2yrs - male (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Under1yr - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	6.0	5.3	5.8	5.3	4.8	4.8	4.8	4.7	4.6	4.5	4.4	4.2	4.1
Oneto2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	2.7	2.5	2.3	2.2	2.0	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7
Over2yrs - female (CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulls(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other Heifers(CH4 Gg/Yr)	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Gilts in Pig	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gilts not yet served	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sows in Pig	$ktCH_4\ yr^{-1}$	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Other Sows for Breeding	$ktCH_4\ yr^{-1}$	0.7	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Boars	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pigs >20kg	$ktCH_4\ yr^{-1}$	4.6	4.6	4.8	4.9	4.9	4.9	4.8	4.8	4.7	4.7	4.6	4.6	4.7
Pigs < 20kg	$ktCH_4\ yr^{-1}$	4.4	4.4	4.3	4.4	4.4	4.4	4.3	4.2	4.2	4.1	4.1	4.1	4.1
Layers	$ktCH_4\ yr^{-1}$	3.3	3.4	3.5	3.9	3.9	4.0	3.9	3.9	3.9	3.9	3.9	3.9	4.0
Broilers	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Turkeys	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Ducks	$ktCH_4\ yr^{-1}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Geese	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total CH4 from Manure Management (CH4 Gg/Yr)		64.7	63.2	66.3	67.4	66.5	66.4	65.7	65.0	64.1	63.4	62.9	62.6	62.8
Manure Methane Emissions		1811.8	1769.2	1856.1	1886.0	1862.1	1858.8	1838.7	1819.4	1794.6	1775.9	1761.5	1752.9	1757.2
Methane Reduction	$ktCO_2\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	30.9	59.0	94.4	127.2	155.1	176.1	183.6
Storage													Mean	82.62
Ammonia Bovines	$t\ NH_3\text{-}N\ yr^{-1}$	6954.1	6882.4	5348.4	5423.6	5305.4	5223.7	5199.1	5189.8	5189.7	5213.3	5240.1	5266.7	5292.0
Ammonia Pigs	$t\ NH_3\text{-}N\ yr^{-1}$	1262.5	1268.7	1311.8	1320.1	1305.5	1295.3	1287.4	1280.8	1274.9	1269.3	1263.7	1258.1	1252.5
Ammonia Poultry	$t\ NH_3\text{-}N\ yr^{-1}$	722.4	766.4	802.7	822.0	834.3	844.4	852.8	858.3	862.4	865.8	869.4	872.5	875.8
Total	$t\ NH_3\text{-}N\ yr^{-1}$	8938.9	8917.5	7462.8	7565.7	7445.2	7363.4	7339.3	7328.9	7327.0	7348.4	7373.2	7397.4	7420.3
Increase in emissions - 20%														
Bovines Uptake	Percentage	0%	0%	0%	0%	0%	0%	3%	4%	8%	11%	15%	18%	21%
Pigs Uptake	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	20%	23%	25%	25%
Poultry Uptake	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	20%	23%	25%	25%
Treated ammonia Bovines	$t\ NH_3\text{-}N\ yr^{-1}$	6954.1	6882.4	5348.4	5423.6	5305.4	5223.7	5228.4	5235.1	5272.8	5325.1	5396.0	5460.1	5510.4
Treated ammonia Pigs	$t\ NH_3\text{-}N\ yr^{-1}$	1262.5	1268.7	1311.8	1320.1	1305.5	1295.3	1300.3	1306.4	1313.2	1320.1	1321.8	1321.0	1315.2
Treated ammonia Poultry	$t\ NH_3\text{-}N\ yr^{-1}$	722.4	766.4	802.7	822.0	834.3	844.4	861.4	875.5	888.2	900.4	909.4	916.1	919.6
Total emissions with aeration	$t\ NH_3\text{-}N\ yr^{-1}$	8938.9	8917.5	7462.8	7565.7	7445.2	7363.4	7390.0	7417.0	7474.1	7545.6	7627.2	7697.3	7745.2
Increase (ammonia-N) tN yr-1	$t\ NH_3\text{-}N\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	-50.7	-88.1	-147.2	-197.2	-254.0	-299.9	-324.8
Increase (Indirect N_2O)	$ktCO_2e\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-0.4	-0.6	-0.8	-1.1	-1.2	-1.4
Total GHG reduction	**$ktCO_2e\ yr^{-1}$**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**30.66**	**58.62**	**93.80**	**126.42**	**154.01**	**174.80**	**182.23**
Pathway 2	**Uptake**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cows	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Other Cows	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	4%	8%	12%	16%	20%
Cattle < 1 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	3%	5%	10%	17%	23%	27%	30%

Cattle 1 - 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Cattle > 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Cattle < 1 yrs - female	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Cattle 1 - 2 yrs - male	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Cattle > 2 yrs - female	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Bulls	Percentage	0%	0%	0%	0%	0%	0%	3%	28%	10%	17%	23%	27%	30%
Dairy Heifers	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Other Heifers	Percentage	0%	0%	0%	0%	0%	0%	0%	0%	4%	8%	12%	16%	20%
Gilts in Pig	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Gilts not yet Served	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Sows in Pig	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Other Sows for Breeding	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Boars	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Pigs 20 Kg +	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Pigs Under 20 Kg	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Layer	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Broiler	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Turkey	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Ducks	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Geese	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Emissions from Manure Management - Gg of CH_4		**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Dairy Cattle	$ktCH_4\ yr^{-1}$	22.7	24.3	26.7	27.9	28.6	28.9	28.8	28.9	29.0	28.5	27.9	28.1	28.4
Other Cows	$ktCH_4\ yr^{-1}$	7.7	7.2	6.6	6.3	5.9	5.5	5.1	4.8	4.4	4.0	3.6	3.3	3.0
Under1yr - male	$ktCH_4\ yr^{-1}$	5.4	4.4	5.2	5.3	5.3	5.3	5.3	5.2	5.0	4.8	4.7	4.6	4.5
Oneto2yrs - male	$ktCH_4\ yr^{-1}$	4.9	4.3	4.2	4.1	3.7	3.7	3.7	3.3	3.5	3.4	3.3	3.2	3.1
Over2yrs -	$ktCH_4\ yr^{-1}$	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Under1yr - female	$ktCH_4\ yr^{-1}$	6.0	5.3	5.8	5.3	4.8	4.8	4.8	4.3	4.6	4.4	4.2	4.1	4.0
Oneto2yrs - female	$ktCH_4\ yr^{-1}$	2.7	2.5	2.3	2.2	2.0	2.0	2.0	1.8	1.9	1.8	1.7	1.7	1.6
Over2yrs - female	$ktCH_4\ yr^{-1}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Bulls	ktCH$_4$ yr^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dairy Heifers	ktCH$_4$ yr^{-1}	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Other Heifers	ktCH$_4$ yr^{-1}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Gilts in Pig	ktCH$_4$ yr^{-1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Gilts not yet served	ktCH$_4$ yr^{-1}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sows in Pig	ktCH$_4$ yr^{-1}	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
Other Sows for Breeding	ktCH$_4$ yr^{-1}	0.7	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Boars	ktCH$_4$ yr^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pigs >20kg	ktCH$_4$ yr^{-1}	4.6	4.6	4.8	4.9	4.9	4.9	4.8	4.8	4.7	4.6	4.4	4.4	4.4
Pigs < 20kg	ktCH$_4$ yr^{-1}	4.4	4.4	4.3	4.4	4.4	4.4	4.3	4.2	4.2	4.0	3.9	3.9	3.9
Layers	ktCH$_4$ yr^{-1}	3.3	3.4	3.5	3.9	3.9	4.0	3.9	3.9	3.9	3.8	3.7	3.7	3.7
Broilers	ktCH$_4$ yr^{-1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Turkeys	ktCH$_4$ yr^{-1}	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ducks	ktCH$_4$ yr^{-1}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Geese	ktCH$_4$ yr^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Manure Emissions (with aeration)	**ktCH$_4$ yr^{-1}**	**64.7**	**63.2**	**66.3**	**67.4**	**66.5**	**66.4**	**65.7**	**63.9**	**64.0**	**62.0**	**60.0**	**59.4**	**59.1**
CO_2 equivalents	**ktCO$_2$e yr^{-1}**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**29.97**	**88.04**	**98.09**	**167.46**	**237.52**	**265.50**	**286.14**
													Mean	**147.65**
Ammonia Bovines	t NH$_3$-N yr^{-1}	6954.1	6882.4	5348.4	5423.6	5305.4	5223.7	5199.1	5189.8	5189.7	5213.3	5240.1	5266.7	5292.0
Ammonia Pigs	t NH$_3$-N yr^{-1}	1262.5	1268.7	1311.8	1320.1	1305.5	1295.3	1287.4	1280.8	1274.9	1269.3	1263.7	1258.1	1252.5
Ammonia Poultry	t NH$_3$-N yr^{-1}	722.4	766.4	802.7	822.0	834.3	844.4	852.8	858.3	862.4	865.8	869.4	872.5	875.8
Total	t NH$_3$-N yr^{-1}	8938.9	8917.5	7462.8	7565.7	7445.2	7363.4	7339.3	7328.9	7327.0	7348.4	7373.2	7397.4	7420.3
Increase in emissions - 20%														
Bovines	Percentage	0%	0%	0%	0%	0%	0%	3%	17%	10%	17%	23%	27%	30%
Pigs	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Poultry	Percentage	0%	0%	0%	0%	0%	0%	5%	10%	15%	25%	35%	38%	40%
Treated ammonia Bovines	t NH$_3$-N yr^{-1}	6954.1	6882.4	5348.4	5423.6	5305.4	5223.7	5225.1	5370.6	5288.3	5385.4	5483.1	5551.1	5609.5

Treated ammonia Pigs	t NH_3-N yr^{-1}	1262.5	1268.7	1311.8	1320.1	1305.5	1295.3	1300.3	1306.4	1313.2	1332.8	1352.2	1353.8	1352.7
Treated ammonia Poultry	t NH_3-N yr^{-1}	722.4	766.4	802.7	822.0	834.3	844.4	861.4	875.5	888.2	909.1	930.2	938.8	945.8
Total emissions with aeration	t NH_3-N yr^{-1}	8938.9	8917.5	7462.8	7565.7	7445.2	7363.4	7386.7	7552.6	7489.7	7627.2	7765.5	7843.7	7908.1
Increase (ammonia-N)	t NH_3-N yr^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	-47.4	-223.6	-162.7	-278.8	-392.3	-446.3	-487.8
Increase (Indirect N_2O)	**ktCO_2e yr^{-1}**	**0.00000**	**0.00000**	**0.00000**	**0.00000**	**0.00000**	**0.00000**	**-0.197**	**-0.931**	**-0.678**	**-1.161**	**-1.634**	**-1.859**	**-2.031**
Total reduction		**0.00000**	**0.00000**	**0.00000**	**0.00000**	**0.00000**	**0.00000**	**30.16**	**88.97**	**98.76**	**168.62**	**239.15**	**267.36**	**288.17**
											Mean	**147.65**

Costs Pathway 1

		2024	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
No farms	**Number**	**928**	**1855**	**4383**	**6899**	**10667**	**15003**	**16638**
Gross equipment Cost	€	10202500	20405000	48207500	75889975	117331500	165027513	183012500
Repayment 8% over 5 years	€	222600	445200	1051800	1655781	2559960	3600600	3993000
NFRV forgone @ 1.20 per kg N	€	60847	105691	176585	236673	304759	359857	389799
Defrayed labour	€	1079610	2159220	5101230	8030539	12415806	17462911	19366050
Discount rate	Percentage	5%	5%	5%	5%	5%	5%	5%
NPV (negative values are cost positive)	**€**	**-€4,054,743**	**-€7,985,906**	**-€18,302,414**	**-€28,493,310**	**-€43,580,539**	**-€60,765,142**	**-€67,315,804**
Euro per tonne	**€ t^{-1} CO_2e**	**€132.25**	**€136.23**	**€195.12**	**€225.38**	**€282.97**	**€347.62**	**€369.39**

Costs Pathway 2

No farms	Number	928	1855	5983	11038	16093	19849	23420
Gross equipment cost Cost		10202500	20405000	65807500	121412500	177017500	218339000	257620000
Repayment 8% over 5 years		222600	445200	1435800	2649000	3862200	4763760	5620800
NFRV forgone @ 1.20 per kg N		56877	268367	195267	334553	470723	535599	585344
Defrayed labour	€	1079610	2159220	6963630	12847650	18731670	23104236	27260880
Discount rate	€	5%	5%	5%	5%	5%	5%	5%
NPV	€	**-€4,024,086**	**-€9,242,050**	**-€24,630,866**	**-€45,244,561**	**-€65,834,190**	**-€80,854,457**	**-€95,040,912**
Euro per tonne	**€ t^{-1} CO_2e**	**€84.90**	**€41.33**	**€151.37**	**€162.29**	**€167.83**	**€181.15**	**€194.84**

Table A1.16: Overview of Modelling Assumptions Used and Results for Land Drainage (Mineral Soils only)

	Unit	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Grassland Area	kha	3680	3697	3643	3626	3613	3600	3589	3579	3570	3562	3556
N_2O Grassland Fertiliser	t N_2O-N yr^{-1}	4616	4603	4281	3696	3077	2828	2888	3460	3299	3135	2886
N_2O Grassland Urine & Dung (PRP)	t N_2O-N yr^{-1}	2723	2741	2696	2670	2685	2703	2717	2736	2755	2771	2786
N_2O Grassland Manure	t N_2O-N yr^{-1}	1636	1657	1622	1608	1616	1621	1620	1625	1629	1632	1631
N_2O Indirect (leaching)	t N_2O-N yr^{-1}	1010	1036	989	960	1000	1020	1036	1044	1048	1048	1061
Total Pasture N_2O	t N_2O-N yr^{-1}	9985	10037	9588	8934	8378	8172	8261	8865	8730	8587	8364
Impeded drained area	kha	1104	1109	1093	1088	1084	1080	1077	1074	1071	1069	1067
Uptake (Pathway 1)	Percentage	0	0	1.0%	2.0%	3.0%	4.0%	6.0%	7.0%	8.0%	9.0%	10.0%
Uptake (Pathway 2)	Percentage	0	0	1.0%	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	25.0%
Area - improved drainage Pathway 1	kha	0	0	10.93	21.76	32.51	43.20	64.59	75.15	85.68	96.18	106.67
Area - improved drainage Pathway 2	kha	0	0	10.93	32.64	65.03	97.19	129.19	161.04	192.78	224.42	266.67
Reduction in direct N_2O fertiliser	%	40%	40%	40%	40%	40%	40%	40%	40%	40%	40%	40%
Reduction in direct N_2O manure& PRP	%	58%	58%	58%	58%	58%	58%	58%	58%	58%	58%	58%
Increase in N leached	%	22%	22%	22%	22%	22%	22%	22%	22%	22%	22%	22%
N_2O emissions with drainage (Pathway 1)	t N_2O-N yr^{-1}	9985	10037	9548	8859	8273	8035	8054	8607	8439	8265	8016
N_2O emissions with drainage (Pathway 2)	t N_2O-N yr^{-1}	9985	10037	9548	8821	8168	7864	7848	8312	8076	7836	7493
Reduction (Pathway 1)	kt CO_2e yr^{-1}	**0**	**0**	**17**	**31**	**44**	**57**	**86**	**107**	**121**	**134**	**145**
Reduction (Pathway 2)	kt CO_2e yr^{-1}	**0**	**0**	**17**	**47**	**88**	**128**	**172**	**230**	**272**	**313**	**363**

Costs – Pathway 1

Low Cost		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Investment @ 1500 per ha	'000 €	0.00	€16,050	€32,100	€48,150	€64,200	€96,300	€112,350	€128,400	€144,450	€160,500	80,2500
uptake rate	Percentage	0%	10%	20%	30%	40%	60%	70%	80%	90%	100%	0.50
Increase in dairy profit per annum	€ yr^{-1}	0.00	€632,752	€1,265,504	€1,898,256	€2,531,009	€3,796,513	€4,429,265	€5,062,017	€5,694,769	6,327,521.43	3,163,760
Increase in beef profit p.a.	€ yr^{-1}	0.00	€468,125	€936,250	€1,404,375	€1,872,500	€2,808,750	€3,276,875	€3,745,000	€4,213,125	4,681,250.00	2,340,625
Total national profit increase	€ yr^{-1}	0.00	€1,100,877	€2,201,754	€3,302,631	€4,403,509	€6,605,263	€7,706,140	€8,807,017	€9,907,894	11,008,771.43	5,504,385
Discount rate	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	0.05
Years		10	20	20	20	20	20	20	20	20	20	19.00
NPV	€ yr^{-1}	€0.00	€4,919,088	€9,838,177	€14,757,265	€19,676,354	€29,514,531	€34,433,619	€39,352,707	€44,271,796	€49,190,884.35	24,595,442
GHG abated	kt CO_2e yr^{-1}	0	17	31	44	57	86	107	121	134	145	74.20
Abatement Cost	**€ t^{-1} CO_2e**	**0**	**-€295.35**	**-€315.13**	**-€336.94**	**-€345.96**	**-€343.12**	**-€320.67**	**-€325.28**	**-€330.17**	**-€339.18**	**-€295.18**
High cost		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Total Investment @ 2500 per ha	'000 €	0.00	-€26,750	-€53,500	-€80,250	-€107,000	-€160,500	-€187,250	-€214,000	-€240,750	-€267,500	-133,750
uptake rate	Percentage	0%	10%	20%	30%	40%	60%	70%	80%	90%	100%	
Increase in dairy profit per annum	€ yr^{-1}	0.00	€632,752	€1,265,504	€1,898,256	€2,531,009	€3,796,513	€4,429,265	€5,062,017	€5,694,769	6,327,521.43	3,163,760
Increase in beef profit p.a.	€ yr^{-1}	0.00	€468,125	€936,250	€1,404,375	€1,872,500	€2,808,750	€3,276,875	€3,745,000	€4,213,125	4,681,250.00	2,340,620
Total national profit increase	€ yr^{-1}	0.00	€1,100,877	€2,201,754	€3,302,631	€4,403,509	€6,605,263	€7,706,140	€8,807,017	€9,907,894	11,008,771.43	5,504,385
Discount rate	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
Years		10	10	10	10	10	10	10	10	10	10	
NPV	€ yr^{-1}	€0.00	-€5,780,912	-€11,561,823	-€17,342,735	-€23,123,646	-€34,685,469	-€40,466,381	-€46,247,293	-€52,028,204	-€57,809,115.65	-28,904,557.82
ktonnes abated	kt CO_2e yr^{-1}	0	17	31	44	57	86	107	121	134	145	74.20
Abatement Cost	€ t^{-1} CO_2e	0	€347.10	€370.35	€395.97	€406.57	€403.24	€376.85	€382.27	€388.02	€398.61	€346.90

Costs – Pathway 2

Low Cost	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Total Investment	'000 €	0.00	€16,050	€32,100	€48,150	€64,200	€96,300	€112,350	€128,400	€144,450	€160,500	€80,250
uptake rate	Percentage	0	1.0%	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	25.0%	
Increase in dairy profit per annum	€ yr^{-1}	0.00	€1,572,938	€3,145,876	€4,718,813	€6,291,751	€9,437,627	€11,010,565	€12,583,502	€14,156,440	€15,729,378	€7,864,689
Increase in beef profit p.a.	€ yr^{-1}	0.00	€1,163,750	€2,327,500	€3,491,250	€4,655,000	€6,982,500	€8,146,250	€9,310,000	€10,473,750	€11,637,500	€5,818,750
Total national profit increase	€ yr^{-1}	0.00	€2,736,688	€5,473,376	€8,210,063	€10,946,751	€16,420,127	€19,156,815	€21,893,502	€24,630,190	€27,366,878	€13,683,439
Discount rate	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
Years		10	10	10	10	10	10	10	10	10	10	
NPV	€ yr^{-1}	€0.00	€10,013,693	€20,027,387	€30,041,080	€40,054,773	€60,082,160	€70,095,853	€80,109,547	€90,123,240	€100,136,933	€50,068,467
ktonnes abated	kt CO_2e yr^{-1}	**0**	**17**	**47**	**88**	**128**	**172**	**230**	**272**	**313**	**363**	**162.88**
Abatement Cost	€ t^{-1} CO_2e	**0**	**-€601.24**	**-€427.68**	**-€342.95**	**-€313.00**	**-€349.24**	**-€304.63**	**-€294.30**	**-€288.06**	**-€276.19**	**-€319.73**
High Cost	**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Total Investment	'000 €	0.00	€26,750	€53,500	€80,250	€107,000	€160,500	€187,250	€214,000	€240,750	€267,500	€133,750
uptake rate	Percentage	0	1.0%	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	25.0%	
Increase in dairy profit per annum	€ yr^{-1}	0.00	€1,572,938	€3,145,876	€4,718,813	€6,291,751	€9,437,627	€11,010,565	€12,583,502	€14,156,440	€15,729,378	7,864,689
Increase in beef profit p.a.	€ yr^{-1}	0.00	€1,163,750	€2,327,500	€3,491,250	€4,655,000	€6,982,500	€8,146,250	€9,310,000	€10,473,750	€11,637,500	5,818,750
Total national profit increase	€ yr^{-1}	0.00	€2,736,688	€5,473,376	€8,210,063	€10,946,751	€16,420,127	€19,156,815	€21,893,502	€24,630,190	€27,366,878	13,683,439
Discount rate	Percentage	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
Years		10	10	10	10	10	10	10	10	10	10	
NPV	€ yr^{-1}	€0.00	-€686,307	-€1,372,613	-€2,058,920	-€2,745,227	-€4,117,840	-€4,804,147	-€5,490,453	-€6,176,760	-€6,863,067	-€3,431,533
ktonnes abated	kt CO_2e yr^{-1}	0	17	47	88	128	172	230	272	313	363	162.88

Abatement Cost	€ t^{-1} CO_2e	0	€41.21	€29.31	€23.50	€21.45	€23.94	€20.88	20.17	€19.74	€18.93	€21.91

Table A1.17: Overview of Modelling Assumptions Used and Results for Use of Digestate from Biomethane Production

Pathway 1					**N**	**P**	**K**						
Storage	**Slurry for digestate**	**Biomethane**			**3.6**	**0.8**	**4**						
	Scenario1	**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Manure storage	Bovine slurry	m^3	0	0	1340	6700	20100	53600	107200	174200	254600	335000	95274
	Pig slurry	m^3	0	0	1340	6700	20100	53600	107200	174200	254600	335000	95274
	Percentage of total bovine slurry	Percentage	0.00%	0.00%	0.01%	0.03%	0.10%	0.27%	0.54%	0.88%	1.30%	1.71%	0.48%
	Percentage of total pig slurry	Percentage	0.00%	0.00%	0.03%	0.16%	0.48%	1.26%	2.51%	4.05%	5.87%	7.66%	2.20%
	Manure Methane (bovine)	kt CH_4 yr^{-1}	0	0	0.0031	0.0154	0.0462	0.1229	0.2458	0.3995	0.5839	0.7683	0.219
	Manure Methane (pig)	kt CH_4 yr^{-1}	0	0	0.0035	0.0177	0.0530	0.1412	0.2824	0.4589	0.6705	0.8821	0.251
	Manure N2O (bovine)	kt N_2O-N yr^{-1}	0	0	0.0001	0.0003	0.0009	0.0023	0.0047	0.0077	0.0112	0.0149	0.004
	Manure N2O (pig)	kt N_2O-N yr^{-1}	0	0	0.0000	0.0001	0.0004	0.0011	0.0022	0.0036	0.0053	0.0069	0.002
	Total Methane Reduction	kt CH_4 yr^{-1}	0	0	0.0059	0.0297	0.0892	0.2378	0.4755	0.7725	1.1289	1.4854	0.422
	Total N2O Reduction	kt N_2O-N yr^{-1}	0	0	0.0001	0.0004	0.0012	0.0031	0.0062	0.0101	0.0149	0.0196	0.006
	Total Manure GHG Reduction	kt CO_2e yr^{-1}	0	0	0.1866	0.9349	2.8061	7.4801	14.9625	24.3182	35.5496	46.7884	13.303
Landspreading													
BAU slurry	Bovine slurry	m^3	0	0	1340	6700	20100	53600	107200	174200	254600	335000	95274
	Pig slurry	m^3	0	0	1340	6700	20100	53600	107200	174200	254600	335000	95274

	N_2O emission factor	kg N_2O-N kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
Bovine	N_2O (field)	kt N_2O-N yr^{-1}	0.00	0.00	0.0001	0.0006	0.0019	0.0052	0.0105	0.0172	0.0253	0.0336	0.00946
	N_2O (indirect)	kt N_2O-N yr^{-1}	0.00	0.00	0.0000	0.0002	0.0005	0.0014	0.0028	0.0045	0.0067	0.0088	0.00249
Pig	N_2O (field)	kt N_2O-N yr^{-1}	0.00	0.00	0.0001	0.0003	0.0008	0.0020	0.0040	0.0065	0.0095	0.0125	0.00356
	N_2O (indirect)	kt N_2O-N yr^{-1}	0.00	0.00	0.0000	0.0000	0.0001	0.0004	0.0008	0.0013	0.0018	0.0024	0.00069
	Total N_2O Landspreading	kt N_2O yr^{-1}	0.0000	0.0000	0.0003	0.0017	0.0053	0.0141	0.0284	0.0464	0.0681	0.0902	0.02545
	NFRV bovine	t N yr^{-1}	0.0000	0.0000	3.29	16.61	50.22	134.79	271.61	444.76	655.16	869.02	244.55
	NFRV pig	t N yr^{-1}	0	0	1.90	9.50	28.50	76.00	151.95	246.86	360.71	474.51	134.99
	Fertiliser Emission Factor	kg N_2O-N kg^{-1} N	1.30%	1.30%	1.30%	1.30%	1.30%	1.30%	1.30%	1.30%	1.30%	1.30%	0.013
	Fertiliser N_2O displaced	kt N_2O yr^{-1}	0.0000	0.0000	0.0001	0.0003	0.0011	0.0028	0.0057	0.0092	0.0136	0.0179	0.0051
Digestate	Digestate generated	m^3	0	0	2680	13400	40200	107200	214400	348400	509200	670000	190548
	available N	TN y^{r-1}	0	0	8.78	43.90	131.70	351.19	702.37	1141.36	1668.14	2194.92	624.24
	Landspreading Ammonia EF	kg NH_3-N kg^{-1} N	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Reduction in emissions from acidification	Percentage	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
	Ammonia (TS)+acid	t NH_3-N yr^{-1}	0.000	0.000	0.219	1.097	3.292	8.780	17.559	28.534	41.703	54.873	15.61
	N_2O Landspreading EF	kg N_2O-N kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
	Landspread N_2O-N	t N_2O-N yr^{-1}	0.000	0.000	0.088	0.439	1.317	3.512	7.024	11.414	16.681	21.949	6.24

	Indirect N_2O (deposition) Emission Factor	kg N_2O-N kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
	Indirect N_2O-N	t N_2O-N yr^{-1}	0.0000	0.000	0.002	0.011	0.033	0.088	0.176	0.285	0.417	0.549	0.156
	Total N_2O (Landspread)	kt N_2O yr^{-1}	0.0000	0.000	0.000	0.001	0.002	0.006	0.011	0.018	0.027	0.035	0.010
	NFRV	TN yr^{-1}	0	0	8.56	42.80	128.40	342.41	684.82	1112.82	1626.44	2140.05	608.63
	Fertiliser N_2O displaced	kt N_2O yr^{-1}	0.0000	0.0000	0.000	0.001	0.002	0.005	0.009	0.015	0.022	0.029	0.008
	Landspread N_2O Reduction	kt N_2O yr^{-1}	0.0000	0.0000	0.000	0.001	0.003	0.008	0.017	0.028	0.041	0.055	0.015
	Net displaced fertiliser N_2O reduction	kt N_2O yr^{-1}	0.0000	0.0000	0.0000	0.0002	0.0007	0.0018	0.0035	0.0056	0.0082	0.0106	0.0031
	Total N_2O reduction	kt N_2O-N yr^{-1}	0.0000	0.0000	0.0003	0.0013	0.0038	0.0102	0.0205	0.0336	0.0494	0.0655	0.018
	Reduction in CO_2e	ktCO_2e yr^{-1}	0.000	0.000	0.066	0.334	1.009	2.705	5.443	8.902	13.096	17.348	4.890
	Total CH_4 and N_2O	**ktCO_2e yr^{-1}**	**0.00**	**0.00**	**0.25**	**1.27**	**3.81**	**10.18**	**20.41**	**33.22**	**48.65**	**64.14**	**18.19**

Costs

Low cost			2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Cost	acidification (€4.44 per m3)	€ yr^{-1}	€0	€0	€11,899	€59,496	€178,488	€475,968	€951,936	€1,546,896	€2,260,848	€2,974,800	€846,033
Saving	fert replacement at €1.20 per kgN	€ yr^{-1}	€0	€0	€10,272	€51,361	€154,083	€410,889	€821,778	€1,335,389	€1,951,723	€2,568,056	€730,355
Net cost		€ yr^{-1}	€0	€0	€1,627	€8,135	€24,405	€65,079	€130,158	€211,507	€309,125	€406,744	€115,678
Euro per tonne	Abatement Cost	€ t^{-1} CO_2e	€0.00	€0.00	€6.43	€6.41	€6.40	€6.39	€6.38	€6.37	€6.35	€6.34	€5.11
High cost													
Cost	acidification (€5.44 per m3)	€ yr^{-1}	€0	€0	€14,579	€72,896	€218,688	€583,168	€1,166,336	€1,895,296	€2,770,048	€3,644,800	€1,036,581
Saving	fert replacement at €2.60 per kgN	€ yr^{-1}	€0	€0	€22,256	€111,282	€333,847	€890,260	€1,780,519	€2,893,344	€4,228,733	€5,564,122	€1,582,436
Net cost		€ yr^{-1}	€0	€0	-€7,677	-€38,386	-€115,159	-€307,092	-€614,183	-€998,048	-€1,458,685	-€1,919,322	-€545,855
Euro per tonne	Abatement Cost	€ t^{-1} CO_2e	€0.00	€0.00	-€30.35	-€30.25	-€30.19	-€30.15	-€30.10	-€30.04	-€29.99	-€29.93	-€24.10

Pathway 2

Scenario 2					N	P	K						
Storage	Slurry for digestate	Biomethane			3.6	0.8	4						
			2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Manure storage	Bovine slurry	m3	0	0	7000	35000	105000	280000	560000	910000	1330000	1750000	497700
	Pig slurry	m3	0	0	7000	35000	105000	280000	560000	910000	1330000	1750000	497700
	Percentage of total bovine slurry	Percentage	0	0	0.0004	0.0018	0.0053	0.0142	0.0284	0.0462	0.0677	0.0893	2.53%
	Percentage of total pig slurry	Percentage	0	0	0.0017	0.0084	0.0249	0.0660	0.1310	0.2113	0.3065	0.4002	11.50%
	Manure Methane (bovine)	kt CH_4 yr^{-1}	0	0	0.0160	0.0803	0.2411	0.6422	1.2843	2.0868	3.0500	4.0135	1.141
	Manure Methane (pig)	kt CH_4 yr^{-1}	0	0	0.0185	0.0923	0.2767	0.7379	1.4754	2.3971	3.5028	4.6080	1.311
	Manure N2O (bovine)	kt N_2O-N yr^{-1}	0	0	0.0003	0.0015	0.0046	0.0122	0.0245	0.0400	0.0587	0.0776	0.022
	Manure N2O (pig)	kt N_2O-N yr^{-1}	0	0	0.0001	0.0007	0.0022	0.0058	0.0116	0.0189	0.0276	0.0363	0.010
	Total Methane Reduction	kt CH_4 yr^{-1}	0	0	0.0310	0.1553	0.4661	1.2420	2.4837	4.0355	5.8975	7.7594	2.207
	Total N2O Reduction	kt N_2O-N yr^{-1}	0	0	0.0004	0.0020	0.0061	0.0162	0.0325	0.0530	0.0777	0.1025	0.029
	Allocation of fugitive Emissions	kt CO_2e yr^{-1}	0	0	0.11	0.55	1.65	4.40	8.80	14.30	20.90	27.50	7.821
	Total Manure GHG Reduction	kt CO_2e yr^{-1}	0	0.00	0.86	4.33	13.01	34.68	69.36	112.74	164.81	216.92	61.67
Landspreading													
BAU slurry	Bovine slurry	m3	0	0	7000	35000	105000	280000	560000	910000	1330000	1750000	497700
	Pig slurry	m3	0	0	7000	35000	105000	280000	560000	910000	1330000	1750000	497700

	N2O emission factor	kg N_2O-N kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0.01
	N2O (field)	kt N_2O-N yr^{-1}	0	0	0.0007	0.0034	0.0101	0.0272	0.0549	0.0899	0.1324	0.1756	0.04943
	N2O (indirect)	kt N_2O-N yr^{-1}	0	0	0.0002	0.0009	0.0027	0.0072	0.0144	0.0236	0.0348	0.0461	0.01298
	N2O (field)	kt N_2O-N yr^{-1}	0	0	0.0003	0.0013	0.0039	0.0105	0.0209	0.0340	0.0497	0.0654	0.01860
	N2O (indirect)	kt N_2O-N yr^{-1}	0	0	0.0001	0.0003	0.0008	0.0020	0.0040	0.0066	0.0096	0.0126	0.00359
	Total N2O Landspreading	kt N_2O yr^{-1}	0	0	0.0018	0.0091	0.0275	0.0737	0.1482	0.2421	0.3559	0.4711	0.13294
	NFRV bovine	t N yr-1	0	0	17.19	86.79	262.33	704.13	1418.85	2323.35	3422.47	4539.66	1277.48
	NFRV pig	t N yr-1	0	0	9.93	49.64	148.90	396.99	793.78	1289.57	1884.31	2478.76	705.19
	Fertiliser Emission Factor	kg N_2O-N kg^{-1} N	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	0.013
	Fertiliser N_2O displaced	kt N_2O yr^{-1}	0	0	0.0004	0.0018	0.0055	0.0147	0.0296	0.0483	0.0709	0.0937	0.0265
Digestate	Digestate generated	m3	0	0	14000	70000	210000	560000	1120000	1820000	2660000	3500000	995400
	available N	TN yr^{-1}	0	0	45.864	229.32	687.96	1834.56	3669.12	5962.32	8714.16	11466	3260.93
	Landspreading Ammonia EF	kg NH3-N kg-1 N	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Reduction in emissions from acidification	Percentage	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
	Ammonia (TS)+acid	t NH_3-N yr^{-1}	0	0	1.15	5.73	17.20	45.86	91.73	149.06	217.85	286.65	81.52
	N2O Landspreading EF	kg N2O-N kg-1 N											
	Landspread N2O-N	t N_2O-N yr^{-1}	0	0	0.46	2.29	6.88	18.35	36.69	59.62	87.14	114.66	32.61

	Indirect N2O (deposition) Emission Factor	kg N_2O-N kg^{-1} N	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
	Indirect N2O-N	t N_2O-N yr^{-1}	0	0	0.011	0.057	0.172	0.459	0.917	1.491	2.179	2.867	0.815
	Total N2O (Landspread)	kt N_2O yr^{-1}	0	0	0.001	0.004	0.011	0.030	0.059	0.096	0.140	0.185	0.053
	NFRV	TN yr^{-1}	0	0	44.7	223.6	670.8	1788.7	3577.4	5813.3	8496.3	11179.4	3179.41
	Fertiliser N_2O displaced	kt N_2O yr^{-1}	0	0	0.001	0.003	0.009	0.024	0.048	0.078	0.113	0.149	0.042
	Landspread N_2O Reduction	kt N_2O yr^{-1}	0	0	0.001	0.005	0.016	0.044	0.089	0.146	0.216	0.286	0.080
	Net displaced fertiliser N2O reduction	kt N_2O yr^{-1}	0	0	0.000	0.001	0.003	0.009	0.018	0.029	0.043	0.056	0.0160
	Total N_2O reduction	kt N_2O-N yr^{-1}	0	0	0.001	0.007	0.020	0.053	0.107	0.175	0.258	0.342	0.096
	Reduction in CO_2e	ktCO_2e yr^{-1}	0	0	0.35	1.75	5.27	14.13	28.44	46.50	68.41	90.62	25.547
	Total CH4 and N2O	**ktCO_2e yr^{-1}**	0	0	1.21	6.08	18.28	48.81	97.80	159.24	233.22	307.54	87.22

Costs

Low N cost		**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Cost	acidification (€4.44 per m3)	€ yr^{-1}	€0	€0	€910,200	€1,176,600	€1,776,000	€1,931,400	€2,109,000	€2,264,400	€2,464,200	€3,418,800	€1,605,060
Saving	fert replacement at €1.20 per kgN	€ yr^{-1}	€0	€0	€53,661	€268,304	€804,913	€2,146,435	€4,292,870	€6,975,914	€10,195,567	€13,415,220	€3,815,289
Net cost	**Net Cost**	**€ yr^{-1}**	**€0**	**€0**	**€856,539**	**€908,296**	**€971,087**	**-€215,035**	**-€2,183,870**	**-€4,711,514**	**-€7,731,367**	**-€9,996,420**	**-€2,210,229**
Euro per tonne	**Abatement Cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€648.22**	**€137.01**	**€48.73**	**-€4.04**	**-€20.49**	**-€27.15**	**-€30.42**	**-€29.84**	**€72.20**
High cost													
Cost	acidification (€5.44 per m3)	€ yr^{-1}	€0	€0	€1,115,200	€1,441,600	€2,176,000	€2,366,400	€2,584,000	€2,774,400	€3,019,200	€4,188,800	€1,966,560
Saving	fert replacement at €2.60 per kgN	€ yr^{-1}	€0	€0	€116,265	€581,326	€1,743,979	€4,650,610	€9,301,219	€15,114,481	€22,090,396	€29,066,310	€8,266,459
Net cost	**Net Cost**	**€ yr^{-1}**	**€0**	**€0**	**€998,935**	**€860,274**	**€432,021**	**-€2,284,210**	**-€6,717,219**	**-€12,340,081**	**-€19,071,196**	**-€24,877,510**	**-€6,299,899**
Euro per tonne	**Abatement Cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€755.99**	**€129.76**	**€21.68**	**-€42.93**	**-€63.01**	**-€71.11**	**-€75.05**	**-€74.25**	**€58.11**

Table A1.18: Overview of Modelling Assumptions Used and Results for Diversification Impacts on Livestock Numbers

Table A1.18a Proportion of livestock reduction via a) organic farming, b) afforestation and c) grass cultivation for biomethane

		P1	P2	Redn stocking
Organics 7.5% farmland	kha	150000	300000	12%
Afforestation	kha	8000	8000	50%
Grassland for biomethane	kha	52000	156000	50%
		Uptake		
Cattle-rearing	no. farms	0.36		
Livestock other	no. farms	0.36		
Sheep rearing	no. farms	0.28		
				Mean
Ave area per farm	ha	21.65		23.002
Ave area per farm	ha	21.4		
Ave area per farm	ha	26.8		
	Cat rear	Live other	sheep	Mean
Suckler cows	16.1	4.8	4	8.64
Heifers	0.75	0.4	1	0.69
< 1 yr old	13.6	15.35	7	12.38
1-2 male	1.8	8.6	0.8	3.97
1-2 female	3.45	8.85	2.2	5.04
> 2yr male	0.15	2.95	0.1	1.14
> 2 yr female	0.55	1.85	0.2	0.92
Bulls	0.5	0.2	0.2	0.31
Ewes	1.2	3.7	92.3	27.61
Other sheep	1.5	3.15	85.5	25.61

Mean net income			
Cattle-rearing	5607.5		
Livestock other	8267		
Sheep rearing	15897.5		
Mean subsidies/direct payments			
Cattle-rearing	9365.5		
Livestock other	9520.5		
Sheep rearing	17218		
Income - subsidies		% applied	Mean
Cattle-rearing	-3758	36%	-2173.88
Livestock other	-1253.5	36%	
Sheep rearing	-1320.5	28%	

Table A1.18b Specific calculations for Diversification Impacts on Livestock Numbers

Pathway 1			**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
BAU emissions		hectares	20000	30000	40000	70000	100000	125000	140000	145000	150000
		hectares		500	1000	2000	3000	4500	6000	7000	8000
		hectares		20000	26000	32000	35500	39500	43000	47500	52000
	Organics	No. farms	869.3	1303.9	1738.5	3042.4	4346.3	5432.9	6084.8	6302.2	6519.5
	Forestry	No. farms		21.7	43.5	86.9	130.4	195.6	260.8	304.2	347.7
	Bio(gas +methane)	No. farms		869.3	1130.0	1390.8	1542.9	1716.8	1868.9	2064.5	2260.1
	Total farms	No. farms	**869**	**2195**	**2912**	**4520**	**6020**	**7345**	**8214**	**8671**	**9127**
	Suckler cows	head	7514	18973	25172	39072	52034	63493	71006	74951	78896
	Heifers	head	603	1523	2021	3137	4178	5098	5701	6018	6334
	< 1 yr old	head	10763	27177	36057	55969	74535	90949	101712	107363	113014
	1-2 male	head	3449	8709	11555	17936	23886	29146	32595	34406	36217
	1-2 female	head	4385	11071	14688	22800	30363	37050	41434	43736	46038
	> 2yr male	head	994	2511	3331	5171	6886	8403	9397	9920	10442
	> 2 yr female	head	800	2019	2679	4159	5538	6758	7557	7977	8397
	Bulls	head	268	676	897	1392	1854	2262	2530	2671	2811
	Ewes	head	23999	60596	80395	124793	166190	202788	226787	239386	251985
	Other sheep	head	22265	56220	74589	115780	154187	188142	210407	222096	233786
Enteric ferm	Suckler cows	kg CH_4 hd^{-1}	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3	73.3
Emission factor	Heifers	kg CH_4 hd^{-1}	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5	58.5
	< 1 yr old	kg CH_4 hd^{-1}	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.6
	1-2 male	kg CH_4 hd^{-1}	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3
	1-2 female	kg CH_4 hd^{-1}	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1	52.1
	> 2yr male	kg CH_4 hd^{-1}	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6
	> 2 yr female	kg CH_4 hd^{-1}	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0

	Bulls	kg CH_4 hd^{-1}	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4	93.4
	Ewes	kg CH_4 hd^{-1}	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
	Other sheep	kg CH_4 hd^{-1}	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Manure management	Suckler cows	kg CH_4 hd^{-1}	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61
Emission factor	Heifers	kg CH_4 hd^{-1}	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11
	< 1 yr old	kg CH_4 hd^{-1}	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81
	1-2 male	kg CH_4 hd^{-1}	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
	1-2 female	kg CH_4 hd^{-1}	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32
	> 2yr male	kg CH_4 hd^{-1}	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49
	> 2 yr female	kg CH_4 hd^{-1}	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	Bulls	kg CH_4 hd^{-1}	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10
	Ewes	kg CH_4 hd^{-1}	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
	Other sheep	kg CH_4 hd^{-1}	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Total methane	Suckler cows	t CH_4 yr^{-1}	608.2	1535.8	2037.6	3162.8	4212.0	5139.5	5747.8	6067.1	6386.4
	Heifers	t CH_4 yr^{-1}	38.3	96.8	128.5	199.4	265.5	324.0	362.4	382.5	402.6
	< 1 yr old	t CH_4 yr^{-1}	402.3	1015.8	1347.7	2091.9	2785.9	3399.4	3801.7	4012.9	4224.1
	1-2 male	t CH_4 yr^{-1}	222.3	561.2	744.5	1155.7	1539.1	1878.0	2100.3	2216.9	2333.6
	1-2 female	t CH_4 yr^{-1}	251.7	635.6	843.2	1308.9	1743.1	2127.0	2378.7	2510.8	2643.0
	> 2yr male	t CH_4 yr^{-1}	38.9	98.2	130.3	202.3	269.4	328.7	367.6	388.1	408.5
	> 2 yr female	t CH_4 yr^{-1}	17.0	42.9	56.9	88.4	117.7	143.6	160.6	169.5	178.4
	Bulls	t CH_4 yr^{-1}	27.7	70.0	92.8	144.1	191.9	234.1	261.8	276.4	290.9
	Ewes	t CH_4 yr^{-1}	205.4	518.7	688.2	1068.2	1422.6	1735.9	1941.3	2049.1	2157.0
	Other sheep	t CH_4 yr^{-1}	127.1	321.0	425.9	661.1	880.4	1074.3	1201.4	1268.2	1334.9

	Total	t CH_4 yr^{-1}	1939.0	4896.0	6495.6	10082.8	13427.6	16384.5	18323.5	19341.5	20359.5
	Total	t N_2O-N yr^{-1}	19.6	49.4	65.5	101.7	135.4	165.3	184.8	195.1	205.3
	Total	kt CO_2e yr^{-1}	62.4	157.7	209.2	324.7	432.4	527.6	590.0	622.8	655.6
Emission allocation	Organics	Percentage	100%	59%	60%	67%	72%	74%	74%	73%	71%
Emission allocation	Forestry	Percentage	0%	1%	1%	2%	2%	3%	3%	4%	4%
Emission allocation	Bio(gas +methane)	Percentage	0%	40%	39%	31%	26%	23%	23%	24%	25%
Reduction	Organics	Percentage	12%	12%	12%	12%	12%	12%	12%	12%	12%
Reduction	Forestry	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduction	Bio(gas +methane)	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduction	Organics	kt CO_2e yr^{-1}	7.5	11.2	15.0	26.2	37.5	46.8	52.4	54.3	56.2
Reduction	Forestry	kt CO_2e yr^{-1}	0.0	0.8	1.6	3.1	4.7	7.0	9.4	10.9	12.5
Reduction	Bio(gas +methane)	kt CO_2e yr^{-1}	0.0	31.2	40.6	49.9	55.4	61.7	67.1	74.1	81.2
	Total	**kt CO_2e yr^{-1}**	**7.5**	**43.2**	**57.1**	**79.3**	**97.6**	**115.5**	**128.9**	**139.4**	**149.8**
Pathway 2		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
BAU emissions		hectares	20000	30000	80000	140000	200000	250000	280000	290000	300000
		hectares		500	1000	2000	3000	4500	6000	7000	8000
		hectares		20000	78000	96000	106500	118500	129000	142500	156000
	Organics	No. farms	869	1304	3477	6085	8693	10866	12170	12604	13039
	Forestry	No. farms		21.7	43.5	86.9	130.4	195.6	260.8	304.2	347.7
	Bio(gas +methane)	No. farms		869.3	3390.1	4172.5	4628.8	5150.4	5606.7	6193.5	6780.3
	Total farms	No. farms	**869**	**2195**	**6911**	**10344**	**13452**	**16212**	**18037**	**19102**	**20167**
	Suckler cows	head	7514	18973	59736	89416	116278	140134	155914	165118	174323
	Heifers	head	603	1523	4796	7179	9336	11251	12518	13257	13996

	< 1 yr old	head	10763	27177	85568	128082	166561	200734	223337	236522	249707
	1-2 male	head	3449	8709	27421	41046	53377	64328	71572	75797	80022
	1-2 female	head	4385	11071	34857	52176	67851	81772	90980	96351	101722
	> 2yr male	head	994	2511	7906	11834	15389	18546	20635	21853	23071
	> 2 yr female	head	800	2019	6358	9517	12376	14915	16594	17574	18554
	Bulls	head	268	676	2128	3186	4143	4993	5555	5883	6211
	Ewes	head	23999	60596	190789	285583	371378	447574	497971	527369	556768
	Other sheep	head	22265	56220	177009	264957	344556	415248	462005	489280	516555
Enteric ferm	Suckler cows	kg CH_4 hd^{-1}	73.34	73.34	73.34	73.34	73.34	73.34	73.34	73.34	73.34
Emission factor	Heifers	kg CH_4 hd^{-1}	58.45	58.45	58.45	58.45	58.45	58.45	58.45	58.45	58.45
	< 1 yr old	kg CH_4 hd^{-1}	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57	32.57
	1-2 male	kg CH_4 hd^{-1}	58.34	58.34	58.34	58.34	58.34	58.34	58.34	58.34	58.34
	1-2 female	kg CH_4 hd^{-1}	52.09	52.09	52.09	52.09	52.09	52.09	52.09	52.09	52.09
	> 2yr male	kg CH_4 hd^{-1}	37.63	37.63	37.63	37.63	37.63	37.63	37.63	37.63	37.63
	> 2 yr female	kg CH_4 hd^{-1}	21.01	21.01	21.01	21.01	21.01	21.01	21.01	21.01	21.01
	Bulls	kg CH_4 hd^{-1}	93.39	93.39	93.39	93.39	93.39	93.39	93.39	93.39	93.39
	Ewes	kg CH_4 hd^{-1}	8	8	8	8	8	8	8	8	8
	Other sheep	kg CH_4 hd^{-1}	5.37	5.37	5.37	5.37	5.37	5.37	5.37	5.37	5.37
Manure management	Suckler cows	kg CH_4 hd^{-1}	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61	7.61
Emission factor	Heifers	kg CH_4 hd^{-1}	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11
	< 1 yr old	kg CH_4 hd^{-1}	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81
	1-2 male	kg CH_4 hd^{-1}	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
	1-2 female	kg CH_4 hd^{-1}	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32	5.32
	> 2yr male	kg CH_4 hd^{-1}	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49

	> 2 yr female	kg CH_4 hd^{-1}	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
	Bulls	kg CH_4 hd^{-1}	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10
	Ewes	kg CH_4 hd^{-1}	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
	Other sheep	kg CH_4 hd^{-1}	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Total methane	Suckler cows	t CH_4 yr^{-1}	608.2	1535.8	4835.4	7237.9	9412.3	11343.5	12620.8	13365.8	14110.9
	Heifers	t CH_4 yr^{-1}	38.3	96.8	304.9	456.3	593.4	715.2	795.7	842.7	889.6
	< 1 yr old	t CH_4 yr^{-1}	402.3	1015.8	3198.2	4787.3	6225.5	7502.7	8347.6	8840.4	9333.2
	1-2 male	t CH_4 yr^{-1}	222.3	561.2	1766.9	2644.8	3439.3	4145.0	4611.7	4884.0	5156.2
	1-2 female	t CH_4 yr^{-1}	251.7	635.6	2001.1	2995.4	3895.2	4694.4	5223.0	5531.4	5839.7
	> 2yr male	t CH_4 yr^{-1}	38.9	98.2	309.3	463.0	602.0	725.6	807.3	854.9	902.6
	> 2 yr female	t CH_4 yr^{-1}	17.0	42.9	135.1	202.2	263.0	316.9	352.6	373.4	394.2
	Bulls	t CH_4 yr^{-1}	27.7	70.0	220.3	329.7	428.8	516.8	574.9	608.9	642.8
	Ewes	t CH_4 yr^{-1}	205.4	518.7	1633.2	2444.6	3179.0	3831.2	4262.6	4514.3	4765.9
	Other sheep	t CH_4 yr^{-1}	127.1	321.0	1010.7	1512.9	1967.4	2371.1	2638.0	2793.8	2949.5
	Total	t CH_4 yr^{-1}	1939.0	4896.0	15415.0	23074.1	30006.0	36162.3	40234.2	42609.5	44984.8
	Total	t N_2O-N yr^{-1}	19.6	49.4	155.5	232.7	302.6	364.7	405.8	429.8	453.7
	Total	kt CO_2e yr^{-1}	62.4	157.7	496.4	743.0	966.2	1164.4	1295.5	1372.0	1448.5
Emission allocation	Organics	Percentage	100%	59%	50%	59%	65%	67%	67%	66%	65%
Emission allocation	Forestry	Percentage	0%	1%	1%	1%	1%	1%	1%	2%	2%
Emission allocation	Bio(gas +methane)	Percentage	0%	40%	49%	40%	34%	32%	31%	32%	34%
Reduction	Organics	Percentage	12%	12%	12%	12%	12%	12%	12%	12%	12%
Reduction	Forestry	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%

Reduction	Bio(gas +methane)	Percentage	60%	60%	60%	60%	60%	60%	60%	60%	60%
Reduction	Organics	kt CO2e yr-1	7.49	11.24	29.97	52.45	74.92	93.65	104.89	108.64	112.38
Reduction	Forestry	kt CO2e yr-1	0.00	0.78	1.56	3.12	4.68	7.02	9.37	10.93	12.49
Reduction	Bio(gas +methane)	kt CO2e yr-1	0.00	37.46	146.10	179.82	199.48	221.96	241.63	266.91	292.20
	Total	**kt CO_2e yr^{-1}**	**7.49**	**49.48**	**177.63**	**235.38**	**279.09**	**322.64**	**355.88**	**386.48**	**417.07**
			2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Costs Pathway 1	Organics	No. farms	869	1304	1739	3042	4346	5433	6085	6302	6519
	Forestry	No. farms	0	22	43	87	130	196	261	304	348
	Bio(gas +methane)	No. farms	0	869	1130	1391	1543	1717	1869	2064	2260
Mean income farm			-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9
Total income (without subsidies)	Organics	€	-€1,889,673	-€2,834,510	-€3,779,346	**7.49**	**43.24**	**363.75**	**470.08**	**549.37**	**630.45**
	Forestry	€	€0	-€47,242	-€94,484	-€188,967	-€283,451	-€425,176	-€566,902	-€661,386	-€755,869
	Bio(gas +methane)	€	€0	-€1,889,673	-€2,456,575	-€3,023,477	-€3,354,170	-€3,732,104	-€4,062,797	-€4,487,974	-€4,913,150
Reduction	Organics	Percentage	12%	12%	12%	12%	12%	12%	12%	12%	12%
Reduction	Forestry	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduction	Bio(gas +methane)	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Cost saving	Organics	€	-€226,761	-€340,141	-€453,522	-€793,663	-€1,133,804	-€1,417,255	-€1,587,325	-€1,644,016	-€1,700,706
	Forestry	€	€0	-€23,621	-€47,242	-€94,484	-€141,725	-€212,588	-€283,451	-€330,693	-€377,935
	Bio(gas +methane)	€	€0	-€944,837	-€1,228,288	-€1,511,739	-€1,677,085	-€1,866,052	-€2,031,399	-€2,243,987	-€2,456,575

	Total	€	-€226,761	-€1,308,599	-€1,729,051	-€2,399,885	-€2,952,614	-€3,495,895	-€3,902,175	-€4,218,695	-€4,535,216
	Abatement Cost	**€ t^{-1} CO_2e**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**	**-€30.27**
			2022	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Costs Pathway 2	Organics	No. farms	869	1304	3477	6085	8693	10866	12170	12604	13039
	Forestry	No. farms	0	22	43	87	130	196	261	304	348
	Bio(gas +methane)	No. farms	0	869	3390	4172	4629	5150	5607	6193	6780
Mean income farm			-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9	-2173.9
Total income (without subsidies)	Organics	€	-€1,889,673	-€2,834,510	-€7,558,693	-€13,227,712	-€18,896,732	-€23,620,914	-€26,455,424	-€27,400,261	-€28,345,097
	Forestry	€	€0	-€47,242	-€94,484	-€188,967	-€283,451	-€425,176	-€566,902	-€661,386	-€755,869
	Bio(gas +methane)	€	€0	-€1,889,673	-€7,369,725	-€9,070,431	-€10,062,510	-€11,196,313	-€12,188,392	-€13,463,921	-€14,739,451
Reduction	Organics	Percentage	12%	12%	12%	12%	12%	12%	12%	12%	12%
Reduction	Forestry	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduction	Bio(gas +methane)	Percentage	50%	50%	50%	50%	50%	50%	50%	50%	50%
Cost saving	Organics	€	-€226,761	-€340,141	-€907,043	-€1,587,325	-€2,267,608	-€2,834,510	-€3,174,651	-€3,288,031	-€3,401,412
	Forestry	€	€0	-€23,621	-€47,242	-€94,484	-€141,725	-€212,588	-€283,451	-€330,693	-€377,935
	Bio(gas +methane)	€	€0	-€944,837	-€3,684,863	-€4,535,216	-€5,031,255	-€5,598,157	-€6,094,196	-€6,731,961	-€7,369,725
	Total	€	-€226,761	-€1,308,599	-€4,639,148	-€6,217,025	-€7,440,588	-€8,645,255	-€9,552,298	-€10,350,685	-€11,149,072
	Abatement Cost	**€ t-1 CO2e**	**-€30.27**	**-€26.45**	**-€26.12**	**-€26.41**	**-€26.66**	**-€26.80**	**-€26.84**	**-€26.78**	**-€26.73**

Table A1.19: Overview of Modelling Assumptions Used and Results for Hedgerow Planting and Management

	Pathway 1	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
	New Hedgerow													
	Biomass	**tCO_2e km^{-1} yr^{-1}**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	**2.706**	
	SOC	**tCO_2e km^{-1} yr^{-1}**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	
	Extra Km per year	km	0	0	0	200	600	1000	2000	8000	16000	18000	20000	5981.82
	Total new hedgerow CO2 sequestered	**$ktCO_2e$ yr^{-1}**	**0**	**0**	**0**	**0.709**	**2.128**	**3.546**	**7.092**	**28.368**	**56.736**	**63.828**	**70.92**	**21.21**
	Unmanaged - regular	tCO_2e km^{-1} yr^{-1}	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	
	Unmanaged-irregular	tCO_2e km^{-1} yr^{-1}	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	
	Extra unmanaged Km (regular)	km	0	0	0	170	510	1700	3400	6800	13600	15300	17000	5316.36
	Extra unmanaged Km (irregular)	km	0	0	0	330	990	3300	6600	13200	26400	29700	33000	10320
	Total managed hedgerow CO_2 sequestered	**$ktCO_2e$ yr^{-1}**	**0.00**	**0.00**	**0.00**	**1.58**	**4.75**	**15.82**	**31.63**	**63.27**	**126.54**	**142.35**	**158.17**	**49.46**
	Total hedgerow sequestration	**$ktCO_2e$ yr^{-1}**	**0**	**0**	**0**	**2.2909**	**6.8727**	**19.363**	**38.726**	**91.636**	**183.272**	**206.181**	**229.09**	**70.68**
Pathway 2	Extra Km per year	km	0	0	0	400	1200	2000	4000	16000	32000	36000	40000	11964
	Total new hedgerow CO2 sequestered	**$ktCO_2e$ yr^{-1}**	**0.00**	**0.00**	**0.00**	**1.42**	**4.26**	**7.09**	**14.18**	**56.74**	**113.47**	**127.66**	**141.84**	**42.42**
	Extra unmanaged Km (regular)	km	0	0	0	255	765	2550	5100	10200	20400	22950	25500	7974.5
	Extra unmanaged Km (irregular)	km	0	0	0	495	1485	4950	9900	19800	39600	44550	49500	15480
	Total managed hedgerow CO_2 sequestered	**$ktCO_2e$ yr^{-1}**	**0.00**	**0.00**	**0.00**	**2.37**	**7.12**	**23.73**	**47.45**	**94.90**	**189.80**	**213.53**	**237.26**	**74.20**
	Total hedgerow sequestration	**$ktCO_2e$ yr^{-1}**	**0.00**	**0.00**	**0.00**	**3.79**	**11.37**	**30.82**	**61.64**	**151.64**	**303.28**	**341.19**	**379.10**	**116.62**
Pathway 1														

Low cost	New Hedge Cost	€	€0	€0	€0	€1,190,000	€3,570,000	€5,950,000	€11,900,000	€47,600,000	€95,200,000	€107,100,000	€119,000,000	€35,591,818
High cost	New Hedge Cost	€	€0	€0	€0	€1,590,000	€4,770,000	€7,950,000	€15,900,000	€63,600,000	€127,200,000	€143,100,000	€159,000,000	€47,555,455
Low cost	**Abatement cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€0**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**
High cost	**Abatement cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€0**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**
Low cost	Hedge management	€	€0	€0	€0	-€7,643	-€22,928	-€76,425	-€152,850	-€305,700	-€611,400	-€687,825	-€764,250	-€239,002
High cost	Hedge management	€	€0	€0	€0	-€10,800	-€32,400	-€108,000	-€216,000	-€432,000	-€864,000	-€972,000	-€1,080,000	-€337,745
Low cost	**Abatement cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€0**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**
High cost	**Abatement cost**	**€ t^{-1} CO_2e**	**€0**	**€0**	**€0**	**-€2.85**	**-€2.85**	**-€3.50**	**-€3.50**	**-€2.85**	**-€2.85**	**-€2.85**	**-€2.85**	**-€2.90**
	Pathway 2													
Low cost	New Hedge Cost	€	0	0	0	€2,380,000	€7,140,000	€11,900,000	€23,800,000	€95,200,000	€190,400,000	€214,200,000	€238,000,000	€71,183,636
High cost	New Hedge Cost	€	0	0	0	€3,180,000	€9,540,000	€15,900,000	€31,800,000	€127,200,000	€254,400,000	€286,200,000	€318,000,000	€95,110,909
Low cost	**Abatement cost**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**	**€1,678**
High cost	**Abatement cost**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**	**€2,242**
Low cost	Hedge management	€	0	0	0	-€7,643	-€22,928	-€76,425	-€152,850	-€305,700	-€611,400	-€687,825	-€764,250	-€239,002
High cost	Hedge management	€	0	0	0	-€10,800	-€32,400	-€108,000	-€216,000	-€432,000	-€864,000	-€972,000	-€1,080,000	-€337,745
Low cost	**Abatement cost**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**	**-€3.22**
High cost	**Abatement cost**	**€ t^{-1} CO_2e**	**0**	**0**	**0**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**	**-€4.55**

Table A1.20: Overview of Modelling Assumptions Used and Results for Grassland Management

	Pathway 1												
	Grassland sequestration	**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
	Clover and MSS	kt CO_2e yr^{-1}	23.60	47.21	70.81	94.42	118.02	141.62	165.23	188.83	212.44	236.04	129.82
	Liming and nutrient management	kt CO_2e yr^{-1}	-14.36	-17.66	-9.89	8.94	27.77	46.60	65.43	84.26	103.09	121.91	41.61
	Total CO_2 sequestration	**kt CO_2e yr^{-1}**	**9.24**	**29.55**	**60.92**	**103.36**	**145.79**	**188.22**	**230.66**	**273.09**	**315.52**	**357.95**	**171.43**
Low cost	Proportional clover cost	€ yr^{-1}	-€980,045	-€1,960,090	-€2,940,135	-€3,920,180	-€4,900,226	-€5,880,271	-€6,860,316	-€7,840,361	-€8,820,406	-€9,800,451	-€5,390,248
	Proportional Lime cost	€ yr^{-1}	-€13,444	-€768,450	-€2,265,019	-€4,503,152	-€6,741,284	-€8,979,417	-€11,217,549	-€13,455,681	-€15,693,814	-€17,931,946	-€8,156,976
High cost	Proportional clover cost	€ yr^{-1}	-€4,575,362	-€9,150,723	-€13,726,085	-€18,301,446	-€22,876,808	-€27,452,169	-€32,027,531	-€36,602,892	-€41,178,254	-€45,753,615	-€25,164,488
	Proportional Lime cost	€ yr^{-1}	€157,455	-€1,455,100	-€4,837,664	-€9,990,238	-€15,155,108	-€20,181,744	-€25,070,144	-€29,820,310	-€34,570,476	-€39,246,861	-€18,017,019
	Total Cost (Low)	**€ yr^{-1}**	**-€993,489**	**-€2,728,540**	**-€5,205,155**	**-€8,423,332**	**-€11,641,510**	**-€14,859,687**	**-€18,077,865**	**-€21,296,042**	**-€24,514,220**	**-€27,732,397**	**-€13,547,224**
	Total Cost (High)	**€ yr^{-1}1**	**-€4,417,907**	**-€10,605,823**	**-€18,563,749**	**-€28,291,684**	**-€38,031,915**	**-€47,633,913**	**-€57,097,675**	**-€66,423,202**	**-€75,748,730**	**-€85,000,476**	**-€43,181,507**
	Abatement Cost (Low)	**€ t^{-1} CO_2e**	**-€107.47**	**-€92.33**	**-€85.44**	**-€81.50**	**-€79.85**	**-€78.95**	**-€78.38**	**-€77.98**	**-€77.69**	**-€77.47**	**-€83.71**
	Abatement Cost (High)	**€ t^{-1} CO_2e**	**-€477.89**	**-€358.88**	**-€304.71**	**-€273.73**	**-€260.87**	**-€253.07**	**-€247.55**	**-€243.23**	**-€240.07**	**-€237.46**	**-€289.75**
	Pathway 2												
	Grassland sequestration	**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
	Clover and MSS	kt CO_2e yr^{-1}	37.872	75.744	113.616	151.488	189.36	227.232	265.104	302.976	340.848	378.72	208.30
	Liming and nutrient management	kt CO_2e yr^{-1}	-20.85	-25.64	-14.36	12.98	40.32	67.66	95.00	122.34	149.68	177.02	60.41
	Total CO_2 sequestration	**kt CO_2e yr^{-1}**	**17.02**	**50.11**	**99.26**	**164.47**	**229.68**	**294.89**	**360.10**	**425.31**	**490.52**	**555.74**	**268.71**
Low Cost	Proportional clover cost	€ yr^{-1}	€456,607	€913,214	€1,369,821	€1,826,428	€2,283,035	€2,739,642	€3,196,249	€3,652,855	€4,109,462	€4,566,069	€2,511,338
	Proportional Lime cost	€ yr^{-1}	-€19,520	-€1,115,762	-€3,288,727	-€6,538,416	-€9,788,104	-€13,037,793	-€16,287,481	-€19,537,169	-€22,786,858	-€26,036,546	-€11,843,638
High cost	Proportional clover cost	€ yr^{-1}	-€2,262,928	-€4,525,857	-€6,788,785	-€9,051,713	-€11,314,642	-€13,577,570	-€15,840,498	-€18,103,427	-€20,366,355	-€22,629,283	-€12,446,106
	Proportional Lime cost	€ yr^{-1}	-€1,367,234	-€7,163,993	-€11,928,861	-€16,936,741	-€21,944,622	-€29,042,389	-€38,143,729	-€48,333,118	-€58,988,859	-€69,762,831	-€30,361,238
	Total Cost (Low)	**€ yr^{-1}**	**€437,087**	**-€202,548**	**-€1,918,907**	**-€4,711,988**	**-€7,505,070**	**-€10,298,151**	**-€13,091,232**	**-€15,884,314**	**-€18,677,395**	**-€21,470,477**	**-€9,332,299**

	Total Cost (High)	**€ yr^{-1}**	**-€3,630,162**	**-€11,689,850**	**-€18,717,646**	**-€25,988,455**	**-€33,259,263**	**-€42,619,959**	**-€53,984,227**	**-€66,436,545**	**-€79,355,214**	**-€92,392,114**	**-€42,807,344**
	Abatement Cost (Low)	**€ t^{-1} CO_2e**	**€25.68**	**-€4.04**	**-€19.33**	**-€28.65**	**-€32.68**	**-€34.92**	**-€36.35**	**-€37.35**	**-€38.08**	**-€38.63**	**-€24.44**
	Abatement Cost (High)	**€ t^{-1} CO_2e**	**-€213.25**	**-€233.29**	**-€188.58**	**-€158.02**	**-€144.81**	**-€144.53**	**-€149.91**	**-€156.21**	**-€161.78**	**-€166.25**	**-€171.66**

Table A1.21: Overview of Modelling Assumptions Used and Results for Water Table Manipulation of Agricultural Peat Soils

Rewetting		**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Pathway 1	hectares rewetted	ha yr^{-1}	0	0	1000	2000	6000	15000	25000	33000	37000	40000	15900
	GHG saving	kt CO_2e yr^{-1}	0.00	0.00	20.20	40.40	121.20	303.00	505.00	666.60	747.40	808.00	321.18
Pathway 2	hectares rewetted	ha yr^{-1}	0	0	1000	2000	8000	18000	32000	54000	72000	80000	26700
	GHG saving	kt CO_2e yr^{-1}	0.00	0.00	20.20	40.40	161.60	363.60	646.40	1090.80	1454.40	1616.00	539.34
	Cost (no restoration)	€ ha^{-1}	€812.79	€812.79	€812.79	€812.79	€812.79	€812.79	€812.79	€812.79	€812.79	€812.79	
	Cost (with restoration)	€ ha^{-1}	€1,795	€1,795	€1,795	€1,795	€1,795	€1,795	€1,795	€1,795	€1,795	€1,795	
Low Cost (Pathway 1)	90% rewet 10% restored	€ yr^{-1}	€0	€0	€911,047	€1,822,093	€5,466,279	€13,665,698	€22,776,163	€30,064,535	€33,708,721	€36,441,860	€14,485,640
High Cost (Pathway 1)	80% rewet 20% restored	€ yr^{-1}	€0	€0	€1,009,302	€2,018,605	€6,055,814	€15,139,535	€25,232,558	€33,306,977	€37,344,186	€40,372,093	€16,047,907
	Low Abatement Cost	€ t^{-1} CO_2e	€0	€0	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10
	High Abatement Cost	€ t^{-1} CO_2e	€0	€0	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97
Low Cost (Pathway 2)	90% rewet 10% restored	€ yr^{-1}	€0	€0	€911,047	€1,822,093	€7,288,372	€16,398,837	€29,153,488	€49,196,512	€65,595,349	€72,883,721	€24,324,942
High Cost (Pathway 2)	80% rewet 20% restored	€ yr^{-1}	€0	€0	€1,009,302	€2,018,605	€8,074,419	€18,167,442	€32,297,674	€54,502,326	€72,669,767	€80,744,186	€26,948,372
	Low Abatement Cost	€ t^{-1} CO_2e	€0	€0	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10	€45.10
	High Abatement Cost	€ t^{-1} CO_2e	€0	€0	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97	€49.97

Table A1.22: Overview of Modelling Assumptions Used and Results for Cover Crops

Pathway 1						**Year**						
Cover Crops		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Area (SB)	kha	120.43	121.35	121.90	122.45	123.15	123.89	124.74	125.57	126.44	127.27	123.72
Area (all Spring Crops)	kha	138.75	140.32	141.68	142.88	144.28	145.62	147.07	148.43	149.80	151.06	144.99
Moderate Uptake (%)	Percentage	3.67%	7.34%	11.01%	14.68%	18.35%	22.02%	25.69%	29.36%	33.03%	33.20%	0.20
Area in cover crops	kha	**0.0**	**5.0**	**13.6**	**21.0**	**26.5**	**32.1**	**37.8**	**43.6**	**49.5**	**50.2**	27.91
N saving	kg N/ha	30	30	30	30	30	30	30	30	30	30	30.00
Total N saved	tN/yr	0.0	150.0	408.0	629.2	794.3	962.0	1133.5	1307.3	1484.4	1504.5	837.3
N2O reduction	t N_2O-N	0.0	2.7	7.2	11.2	14.1	17.1	20.1	23.2	26.3	26.7	14.85
N2O reduction	kt CO_2-e	0.0	1.2	3.4	5.2	6.6	8.0	9.4	10.9	12.3	12.5	6.95
Reduced CO2 loss	kt CO_2-e	0.0	4.6	12.5	19.2	24.3	29.4	34.6	39.9	45.4	46.0	25.58
Total GHG savings	kt CO_2-e	0.0	5.8	15.9	24.5	30.9	37.4	44.0	50.8	57.7	58.5	32.54
Pathway 2 Uptake (%)	**Percentage**	**4.6%**	**9.0%**	**14.1%**	**18.5%**	**22.9%**	**27.2%**	**31.6%**	**36.0%**	**43.0%**	**46.4%**	**0.25**
Area in cover crops	kha	**0.0**	**8.3**	**16.6**	**24.9**	**33.2**	**41.5**	**49.8**	**58.1**	**66.4**	**75.0**	37.38
N saving	kg N/ha	30	30	30	30	30	30	30	30	30	30	30.00
Total N saved	tN/yr	0.0	249.0	498.0	747.0	996.0	1245.0	1494.0	1743.0	1992.0	2250.0	1121.4
N2O reduction	t N_2O-N	0.0	4.4	8.8	13.2	17.7	22.1	26.5	30.9	35.3	39.9	19.88
N2O reduction	kt CO_2-e	0.0	2.1	4.1	6.2	8.3	10.3	12.4	14.5	16.5	18.7	9.31
Reduced CO2 loss	kt CO_2-e	0.0	7.6	15.2	22.8	30.4	38.0	45.7	53.3	60.9	68.8	34.27
Total GHG savings	kt CO_2-e	0.0	9.7	19.4	29.0	38.7	48.4	58.1	67.7	77.4	87.4	43.58
Cover crop seed	euro/ha	€37	€37	€37	€37	€37	€37	€37	€37	€37	€37	37.00
Cover crop seed	euro/ha	€47	€47	€47	€47	€47	€47	€47	€47	€47	€47	47.00
Fuel usage 0.53 euro/l	euro/ha	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73	€14.73
Fuel usage 1.30 euro/l	euro/ha	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14	€36.14
Pathway 1 cost												
Low Cost	*000 euro/yr*	*€0*	*€259*	*€704*	*€1,085*	*€1,370*	*€1,659*	*€1,955*	*€2,254*	*€2,560*	*€2,594*	€1,444
High Cost	*000 euro/yr*	*€0*	*€416*	*€1,131*	*€1,744*	*€2,201*	*€2,666*	*€3,141*	*€3,623*	*€4,114*	*€4,170*	€2,320

Monetary N saving (1.2 euro/kgN)	*000 euro/yr*	*€0*	*€180*	*€490*	*€755*	*€953*	*€1,154*	*€1,360*	*€1,569*	*€1,781*	*€1,805*	*€1,005*
Monetary N saving (2.6 euro/kgN)	*000 euro/yr*	*€0*	*€390*	*€1,061*	*€1,636*	*€2,065*	*€2,501*	*€2,947*	*€3,399*	*€3,859*	*€3,912*	*€2,177.03*
Total cost (low)	**000 euro/yr**	**€0.00**	**€78.67**	**€213.98**	**€330.02**	**€416.58**	**€504.52**	**€594.47**	**€685.66**	**€778.49**	**€789.07**	**€439.15**
Total cost (high)	**000 euro/yr**	**€0.00**	**€25.70**	**€69.90**	**€107.81**	**€136.09**	**€164.82**	**€194.20**	**€223.99**	**€254.32**	**€257.77**	**€143.46**
Cost per tCO2 abated (low)	**euro /tCO2e**	**€0.00**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€12.15**
Cost per tCO2 abated (high)	**euro /tCO2e**	**€0.00**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€3.97**
Pathway 2												
Low Cost	*000 euro/yr*	*€0.00*	*€429.39*	*€858.78*	*€1,288.18*	*€1,717.57*	*€2,146.96*	*€2,576.35*	*€3,005.75*	*€3,435.14*	*€3,880.05*	*€1,933.82*
High Cost	*000 euro/yr*	*€0.00*	*€690.06*	*€1,380.12*	*€2,070.19*	*€2,760.25*	*€3,450.31*	*€4,140.37*	*€4,830.43*	*€5,520.50*	*€6,235.50*	*€2,733.97*
Monetary N saving (1.2 euro/kgN)	*000 euro/yr*	*€0.00*	*€298.80*	*€597.60*	*€896.40*	*€1,195.20*	*€1,494.00*	*€1,792.80*	*€2,091.60*	*€2,390.40*	*€2,700.00*	*€1,345.68*
Monetary N saving (2.6 euro/kgN)	*000 euro/yr*	*€0.00*	*€647.40*	*€1,294.80*	*€1,942.20*	*€2,589.60*	*€3,237.00*	*€3,884.40*	*€4,531.80*	*€5,179.20*	*€5,850.00*	*€2,915.64*
Total cost (low)	000 euro/yr	**€0.00**	**€130.59**	**€261.18**	**€391.78**	**€522.37**	**€652.96**	**€783.55**	**€914.15**	**€1,044.74**	**€1,180.05**	**€588.14**
Total cost (high)	000 euro/yr	**€0.00**	**€42.66**	**€85.32**	**€127.99**	**€170.65**	**€213.31**	**€255.97**	**€298.63**	**€341.30**	**€385.50**	**€192.13**
Cost per tCO2 abated (low)	**euro /tCO2e**	**€0.00**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€13.50**	**€12.15**
Cost per tCO2 abated (high)	**euro /tCO2e**	**€0.00**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€4.41**	**€3.97**

Table A1.23: Overview of Modelling Assumptions Used and Results for Straw Incorporation

Pathway 1						**Year**						
Straw Incorporation		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Area -Straw incorporated	kha	**5**	**10**	**15**	**20**	**26.5**	**33**	**39.5**	**46**	**52.5**	**60**	
N saving	kg N/ha	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Total N saved	tN yr^{-1}	72	144	216	288	381.6	475.2	568.8	662.4	756	864	442.8
N2O reduction	t N_2O-N	1.3	2.6	3.8	5.1	6.8	8.4	10.1	11.7	13.4	15.3	7.9
N2O reduction	kt CO_2-e	0.6	1.2	1.8	2.4	3.2	3.9	4.7	5.5	6.3	7.2	3.7
Reduced CO2 loss	kt CO_2-e	5.4	10.0	15.0	20.0	26.5	33.0	39.5	46.0	52.5	60.0	30.79
Total GHG savings	**kt CO_2-e**	**6.0**	**11.2**	**16.8**	**22.4**	**29.7**	**36.9**	**44.2**	**51.5**	**58.8**	**67.2**	**34.47**
Pathway 2						**Year**						
Straw Incorporation		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Area -Straw incorporated	kha	**5**	**10**	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	
N saving	kg N/ha	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Total N saved	tN yr^{-1}	72	144	216	360	504	648	792	936	1080	1224	597.6
N2O reduction	t N_2O-N	1.3	2.6	3.8	6.4	8.9	11.5	14.0	16.6	19.1	21.7	10.6
N2O reduction	kt CO_2-e	0.6	1.2	1.8	3.0	4.2	5.4	6.6	7.8	9.0	10.2	5.0
Reduced CO2 loss	kt CO-e	5.4	10.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	41.54
Total GHG savings	**kt CO_2-e**	**6.0**	**11.2**	**16.8**	**28.0**	**39.2**	**50.4**	**61.6**	**72.8**	**84.0**	**95.2**	**46.50**

Costs

			2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
Pathway 1	Straw yield per ha	t/ha	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Low cost	Total straw yield	tDM/yr	18000	36000	54000	72000	95400	118800	142200	165600	189000	216000	110,700
	Straw cost 16 euro bale @ 150kgDM/bale	€	1,920,000	3,840,000	5,760,000	7,680,000	10,176,000	12,672,000	15,168,000	17,664,000	20,160,000	23,040,000	11,808,000
	Cost chopping	€	270,000	540,000	810,000	1,080,000	1,431,000	1,782,000	2,133,000	2,484,000	2,835,000	3,240,000	1,660,500
	Cost saving (baling, handling, turning @ 6.5 euro per bale)	€	780000	1560000	2340000	3120000	4134000	5148000	6162000	7176000	8190000	9360000	4,797,000
	N,P, K saving	€	255,600	511,200	766,800	1,022,400	1,354,680	1,686,960	2,019,240	2,351,520	2,683,800	3,067,200	1,571,940
	Transport saving	€	360000	720000	1080000	1440000	1908000	2376000	2844000	3312000	3780000	4320000	2,214,000
	Total Cost	**€**	**794,400**	**1,588,800**	**2,383,200**	**3,177,600**	**4,210,320**	**5,243,040**	**6,275,760**	**7,308,480**	**8,341,200**	**9,532,800**	**4,885,560**
	Euro per tonne	**€ t-1 CO2e**	**132**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**141**
High cost	Straw cost 16 euro bale @ 150kgDM/bale	€	2,520,000	5,040,000	7,560,000	10,080,000	13,356,000	16,632,000	19,908,000	23,184,000	26,460,000	30,240,000	15,498,000
Pathway 1	Cost chopping	€	288,000	576,000	864,000	1,152,000	1,526,400	1,900,800	2,275,200	2,649,600	3,024,000	3,456,000	1,771,200
	Cost saving (baling, handling, turning @ 7.5 euro per bale)	€	900000	1800000	2700000	3600000	4770000	5940000	7110000	8280000	9450000	10800000	5,535,000
	N,P, K saving	€	536,400	1,072,800	1,609,200	2,145,600	2,842,920	3,540,240	4,237,560	4,934,880	5,632,200	6,436,800	3,298,860
	Transport saving @ 4 per bale	€	480000	960000	1440000	1920000	2544000	3168000	3792000	4416000	5040000	5760000	2,952,000
	Total Cost	**€**	**891,600**	**1,783,200**	**2,674,800**	**3,566,400**	**4,725,480**	**5,884,560**	**7,043,640**	**8,202,720**	**9,361,800**	**10,699,200**	**5,483,340**

	Euro per tonne	**€ t-1 CO2e**	**149**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**158**
Pathway 2	Straw yield per ha	t/ha	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Low cost	tDM/yr	tDM/yr	18000	36000	54000	90000	126000	162000	198000	234000	270000	306000	149,400
	Straw cost 16 euro bale @ 150kgDM/bale	€	1,920,000	3,840,000	5,760,000	9,600,000	13,440,000	17,280,000	21,120,000	24,960,000	28,800,000	32,640,000	15,936,000
	Cost chopping	€	270,000	540,000	810,000	1,350,000	1,890,000	2,430,000	2,970,000	3,510,000	4,050,000	4,590,000	2,241,000
	Cost saving (baling, handling, turning @ 6.5 euro per bale)	€	780000	1560000	2340000	3900000	5460000	7020000	8580000	10140000	11700000	13260000	6,474,000
	N,P, K saving	€	255,600	511,200	766,800	1,278,000	1,789,200	2,300,400	2,811,600	3,322,800	3,834,000	4,345,200	2,121,480
	Transport saving	€	360000	720000	1080000	1800000	2520000	3240000	3960000	4680000	5400000	6120000	2,988,000
	Total Cost	**€**	**794,400**	**1,588,800**	**2,383,200**	**3,972,000**	**5,560,800**	**7,149,600**	**8,738,400**	**10,327,200**	**11,916,000**	**13,504,800**	**6,593,520**
	Euro per tonne	**€ t-1 CO2e**	**132**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**142**	**141**
High cost	Straw cost 16 euro bale @ 150kgDM/bale	€	2,520,000	5,040,000	7,560,000	12,600,000	17,640,000	22,680,000	27,720,000	32,760,000	37,800,000	42,840,000	20,916,000
Pathway 2	Cost chopping	€	288,000	576,000	864,000	1,440,000	2,016,000	2,592,000	3,168,000	3,744,000	4,320,000	4,896,000	2,390,400
	Cost saving (baling, handling, turning @ 7.5 euro per bale)	€	900000	1800000	2700000	4500000	6300000	8100000	9900000	11700000	13500000	15300000	7,470,000
	N,P, K saving	€	536,400	1,072,800	1,609,200	2,682,000	3,754,800	4,827,600	5,900,400	6,973,200	8,046,000	9,118,800	4,452,120
	Transport saving @ 4 per bale	€	480000	960000	1440000	2400000	3360000	4320000	5280000	6240000	7200000	8160000	3,984,000
	Total Cost	**€**	**891,600**	**1,783,200**	**2,674,800**	**4,458,000**	**6,241,200**	**8,024,400**	**9,807,600**	**11,590,800**	**13,374,000**	**15,157,200**	**7,400,280**
	Euro per tonne	**€ t-1 CO2e**	**149**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**159**	**158**

Table A1.24: Overview of Modelling Assumptions Used and Results for Enhanced Manure Application of Arable Soils

Manure to tillage			**Pathway 1**											
			2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	
	Total Bovine Slurry	m^3	**20319323**	**20319323**	**20073282**	**19858764**	**19824519**	**19796428**	**19740723**	**19718738**	**19687104**	**19643253**	**19587812**	
	Total Pig Slurry	m^3	**4158462**	**4158462**	**4154569**	**4166600**	**4187117**	**4213262**	**4242790**	**4274206**	**4306293**	**4339121**	**4372693**	
	Total Cow slurry N Tonnes	$tN\ yr^{-1}$	**48766.38**	**48766**	**48176**	**47661**	**47579**	**47511**	**47378**	**47325**	**47249**	**47144**	**47011**	
	Total Pig slurry N Tonnes	$tN\ yr^{-1}$	**10812**	**10812**	**10802**	**10833**	**10887**	**10954**	**11031**	**11113**	**11196**	**11282**	**11369**	
	Total Cow slurry ammonical N Tonnes	$tNH_4\text{-}N\ yr^{-1}$	**20319.32**	**20319**	**20073**	**19859**	**19825**	**19796**	**19741**	**19719**	**19687**	**19643**	**19588**	
	Total Pig slurry ammonical N Tonnes	$tNH_4\text{-}N\ yr^{-1}$	**8732.769**	**8733**	**8725**	**8750**	**8793**	**8848**	**8910**	**8976**	**9043**	**9112**	**9183**	
	Total Slurry volume	m^3	24477785	24477785	24227850	24025364	24011635	24009690	23983513	23992944	23993397	23982375	23960506	
	Total ammonical N	$tNH_4\text{-}N\ yr^{-1}$	29052.1	29052.1	28797.9	28608.6	28617.5	28644.3	28650.6	28694.6	28730.3	28755.4	28770.5	
	C content	$tC\ yr^{-1}$	602966	602966	596408	590937	590361	590038	589040	588962	588640	588008	587081	
	Tillage area (kha)	hectares	288.3456	296.1518	301.6101	305.7372	310.0693113	313.7789691	320.7301598	324.1569021	327.551581	330.4968431	333.2725428	
	Frac spread on tillage	Percentage	0	0	0	0.005	0.01	0.015	0.02	0.04	0.06	0.07	0.08	
	C spread pa	$tC\ yr^{-1}$	0	0	0	2954.685	5903.611586	8850.568392	11780.79442	23558.47953	35318.41332	41160.54809	46966.50675	
	Tillage area @ 30 m3/ha ha	hectares	0	0	0	4004.227	8003.878454	12004.845	15989.00851	31990.59239	47986.7931	55958.87438	63894.68147	

	NH3 loss - trailing hose EF	kg NH_3-N kg^{-1} N	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	0.1341	
	Nox loss EF	kg Nox-N kg^{-1} N	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	
	NH3 Loss	tNH_3-N yr^{-1}	0	0	0	19.18	38.38	57.62	76.84	153.92	231.16	269.93	308.65	
	NOx loss	tNox-N yr^{-1}	0	0	0	3.58	7.15	10.74	14.33	28.69	43.10	50.32	57.54	
	Total loss	tN yr^{-1}	0	0	0	22.8	45.5	68.4	91.2	182.6	274.3	320.2	366.2	
	NFRV	tN yr^{-1}	0	0	0	120	241	361	482	965	1450	1693	1935	
	N_2O displaced	t N_2O-N yr^{-1}	0	0	0	1.68	3.37	5.06	6.75	13.51	20.29	23.70	27.10	**Mean**
	GHG reduction (CO2e)	kt CO_2e yr^{-1}	0	0	0	0.70	1.40	2.11	2.81	5.63	8.45	9.87	11.28	3.84
	SOC	tC yr^{-1}	0	0	0	355	708	1062	1414	2827	4238	4939	5636	1925
	CO2e (ktCO2e yr-1)	kt CO_2e yr^{-1}	0	0	0	1.30	2.60	3.89	5.18	10.37	15.54	18.11	20.67	7.06
	Total Reduction	**kt CO_2e yr^{-1}**	**0**	**0**	**0**	**2.00**	**4.00**	**6.00**	**7.99**	**15.99**	**23.99**	**27.98**	**31.95**	**10.90**
Low Cost	Cost - transport		-	-	-	€379,601	€758,768	€1,138,059	€1,515,758	€3,032,708	€4,549,148	€5,304,901	€6,057,216	€2,842,020
	spreading		-	-	-	€336,355	€672,326	€1,008,407	€1,343,077	€2,687,210	€4,030,891	€4,700,545	€5,367,153	€2,518,245
	N saving		-	-	-	€144,342	€288,773	€433,566	€578,215	€1,158,205	€1,739,471	€2,031,156	€2,322,536	€1,087,033
	P saving		-	-	-	€192,203	€384,186	€576,233	€767,472	€1,535,548	€2,303,366	€2,686,026	€3,066,945	€1,438,997
	K saving		-	-	-	€360,380	€720,349	€1,080,436	€1,439,011	€2,879,153	€4,318,811	€5,036,299	€5,750,521	€2,698,120
	Net Cost		-	-	-	€19,031	€37,785	€56,232	€74,137	€147,011	€218,390	€251,967	€284,367	€136,115
	Abatement Cost		-	-	-	€9.51	€9.44	€9.37	€9.28	€9.19	€9.10	€9.01	€8.90	€9.23
High Cost	Cost - transport		-	-	-	€559,791	€1,118,942	€1,678,277	€2,235,263	€4,472,285	€6,708,554	€7,823,051	€8,932,476	€ 4,191,080
	spreading			-	-	€420,444	€840,407	€1,260,509	€1,678,846	€3,359,012	€5,038,613	€5,875,682	€6,708,942	€ 3,147,807
	N saving		-	-	-	€312,741	€625,675	€939,392	€1,252,798	€2,509,444	€3,768,855	€4,400,837	€5,032,162	€ 2,355,238

	P saving		-	-	-	€371,913	€743,400	€1,115,010	€1,485,059	€2,971,286	€4,457,013	€5,197,460	€5,934,538	€ 2,784,460
	K saving		-	-	-	€480,507	€960,465	€1,440,581	€1,918,681	€3,838,871	€5,758,415	€6,715,065	€7,667,362	€ 3,597,494
	Net Cost		-	-	-	-€184,926	-€370,191	-€556,197	-€742,429	-€1,488,304	-€2,237,116	-€2,614,630	-€2,992,644	-€ 1,398,305
	Abatement Cost		**-**	**-**	**-**	**-€92.40**	**-€92.54**	**-€92.69**	**-€92.89**	**-€93.06**	**-€93.25**	**-€93.45**	**-€93.67**	**-€92.99**
Manures to cropland		**Pathway 2**												
			2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
	Total Bovine Slurry	m^3	**20319323**	**20319323**	**20073282**	**19858764**	**19824519**	**19796428**	**19740723**	**19718738**	**19687104**	**19643253**	**19587812**	
	Total Pig Slurry	m^3	**4158462**	**4158462**	**4154569**	**4166600**	**4187117**	**4213262**	**4242790**	**4274206**	**4306293**	**4339121**	**4372693**	
	Total Cow slurry N Tonnes	$tN\ yr^{-1}$	**48766.38**	**48766**	**48176**	**47661**	**47579**	**47511**	**47378**	**47325**	**47249**	**47144**	**47011**	
	Total Pig slurry N Tonnes	$tN\ yr^{-1}$	**10812**	**10812**	**10802**	**10833**	**10887**	**10954**	**11031**	**11113**	**11196**	**11282**	**11369**	
	Total Cow slurry ammonical N Tonnes	$tNH_4\text{-}N\ yr^{-1}$	**20319.32**	**20319**	**20073**	**19859**	**19825**	**19796**	**19741**	**19719**	**19687**	**19643**	**19588**	
	Total Pig slurry ammonical N Tonnes	$tNH_4\text{-}N\ yr^{-1}$	**8732.769**	**8733**	**8725**	**8750**	**8793**	**8848**	**8910**	**8976**	**9043**	**9112**	**9183**	
	Total Slurry volume	m^3	24477785	24477785	24227850	24025364	24011635	24009690	23983513	23992944	23993397	23982375	23960506	
	Total ammonical N	$tNH_4\text{-}N\ yr^{-1}$	29052	29052	28798	28609	28617	28644	28651	28695	28730	28755	28770	
	C content	$tC\ yr^{-1}$	602966	602966	596408	590937	590361	590038	589040	588962	588640	588008	587081	
	Tillage area (kha)	hectares	288.3	296.2	301.6	305.7	310.1	313.8	320.7	324.2	327.6	330.5	333.3	

	Frac spread on tillage	Percentage	0%	0%	0%	1%	1%	2%	4%	8%	10%	12%	14%	
	C spread pa	tC yr^{-1}	0	0	0	2955	5904	11801	23562	47117	58864	70561	82191	
	Tillage area @ 30 m3/ha ha	hectares	0	0	0	4004	8004	16006	31978	63981	79978	95929	111816	
	NH3 loss - trailing hose EF	kg NH_3-N kg^{-1} N	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	
	Nox loss EF	kg Nox-N kg^{-1} N	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	
	NH3 Loss	tNH_3-N yr^{-1}	0	0	0	19.2	38.4	76.8	153.7	307.8	385.3	462.7	540.1	
	NOx loss	tNox-N yr^{-1}	0	0	0	3.6	7.2	14.3	28.7	57.4	71.8	86.3	100.7	
	Total loss	tN yr^{-1}	0	0	0	22.8	45.5	91.1	182.3	365.2	457.1	549.0	640.8	
	NFRV	tN yr^{-1}	0	0	0	120.3	240.6	481.7	963.7	1930.3	2415.9	2901.7	3387.0	
	N_2O displaced	t N_2O-N yr^{-1}	0	0	0	1.68	3.37	6.74	13.49	27.02	33.82	40.62	47.42	
	GHG reduction (CO2e)	kt CO_2e yr^{-1}	0	0	0	0.70	1.40	2.81	5.62	11.25	14.08	16.92	19.75	6.59
	SOC	tC yr^{-1}	0	0	0	354.56	708.43	1416.09	2827.39	5654.04	7063.68	8467.31	9862.97	3304.95
	CO2e (ktCO2e yr-1)	kt CO_2e yr^{-1}	0	0	0	1.300	2.598	5.192	10.367	20.731	25.900	31.047	36.164	12.12
	Total Reduction	**kt CO_2e yr^{-1}**	**0**	**0**	**0**	**2.00**	**4.00**	**8.00**	**15.99**	**31.99**	**39.99**	**47.96**	**55.91**	18.71
Low Cost	Cost - transport	€ yr^{-1}	-	-	-	€379,601	€758,768	€1,517,412	€3,031,516	€6,065,416	€7,581,913	€9,094,116	€10,600,128	€4,878,609
	spreading	€ yr^{-1}	-	-	-	€336,355	€672,326	€1,344,543	€2,686,153	€5,374,420	€6,718,151	€8,058,078	€9,392,518	€4,322,818
	N saving	€ yr^{-1}	-	-	-	€144,342	€288,773	€578,087	€1,156,429	€2,316,409	€2,899,119	€3,481,981	€4,064,439	€1,866,197
	P saving	€ yr^{-1}	-	-	-	€192,203	€384,186	€768,310	€1,534,945	€3,071,097	€3,838,943	€4,604,616	€5,367,153	€2,470,182
	K saving	€ yr^{-1}	-	-	-	€360,380	€720,349	€1,440,581	€2,878,022	€5,758,307	€7,198,019	€8,633,655	€10,063,412	€4,631,591
	Net Cost	€ yr^{-1}	-	-	-	€19,031	€37,785	€74,976	€148,274	€294,023	€363,983	€431,943	€497,642	€233,457

	Abatement Cost	€ $t^{-1}CO_2e$	-	-	-	€9.51	€9.44	€9.37	€9.28	€9.19	€9.10	€9.01	€8.90	€9.23
High Cost	Cost - transport	€ yr^{-1}	-	-	-	€559,791	€1,118,942	€2,237,703	€4,470,527	€8,944,570	€11,180,923	€13,410,944	€15,631,834	€ 7,194,404
	spreading	€ yr^{-1}		-	-	€420,444	€840,407	€1,680,678	€3,357,692	€6,718,024	€8,397,689	€10,072,597	€11,740,648	€ 5,403,522
	N saving	€ yr^{-1}	-	-	-	€312,741	€625,675	€1,252,523	€2,505,597	€5,018,887	€6,281,425	€7,544,292	€8,806,284	€ 4,043,428
	P saving	€ yr^{-1}	-	-	-	€371,913	€743,400	€1,486,680	€2,970,118	€5,942,572	€7,428,356	€8,909,932	€10,385,442	€ 4,779,802
	K saving	€ yr^{-1}	-	-	-	€480,507	€960,465	€1,920,775	€3,837,362	€7,677,742	€9,597,359	€11,511,540	€13,417,883	€ 6,175,454
	Net Cost	€ yr^{-1}	-	-	-	-€184,926	-€370,191	-€741,596	-€1,484,858	-€2,976,608	-€3,728,527	-€4,482,222	-€5,237,127	-€ 2,400,757
	Abatement Cost	€ $t^{-1}CO_2e$	-	-	-	-€92.40	-€92.54	-€92.69	-€92.89	-€93.06	-€93.25	-€93.45	-€93.67	-€92.99

Table A1.25: Overview of Modelling Assumptions Used and Results for Biomethane Production

Pathway 1												
Low Cost	**Units**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Gas Energy	Gwh	0	0	20	20	320	320	640	640	640	1000	
No of Plants		0	0	1	1	16	16	32	32	32	50	
Volume Methane	m^3	0	0	1895734.597	1895734.597	30331753.55	30331753.55	60663507.11	60663507.11	60663507.11	94786729.86	
Capital Expenditure	€	0	0	-5816000	-5816000	-93056000	-93056000	-186112000	-186112000	-186112000	-290800000	
Interest	€	0	0	262031	262031	4192491	4192491	8384983	8384983	8384983	13101535	
Operating Cost	€	0	0	-2330031	-2330031	-37280491	-37280491	-74560983	-74560983	-74560983	-116501535	
Annual Revenue	€	0	0	2753081	2753081	44049289	44049289	88098578	88098578	88098578	137654028	
Annual Net Cash Flow 7c per kWh gas and 5c per kwh heat	€	0	0	423050	423050	6768798	6768798	13537596	13537596	13537596	21152493	
Discount Rate	Percentage			0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Years	years			15	15	15	15	15	15	15	15	
NPV	€			2643603	2643603	42298383	42298383	84596816	84596816	84596816	132182553	65430338
GHG abated (ktonne)	kt CO_2e yr^{-1}			5.33	5.33	85.25	85.25	170.50	170.50	170.50	266.40	131.87
euro per tonne abated	€ t-1 CO2e			496.18	496.18	496.18	496.18	496.18	496.18	496.18	496.18	496.18
Pathway 1												
High Cost	**Units**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Gas Energy	Gwh	0	0	20	20	320	320	640	640	640	1000	
No of Plants		0	0	1	1	16	16	32	32	32	50	
Volume Methane	m^3	0	0	1895735	1895735	30331754	30331754	60663507	60663507	60663507	94786730	

Capital Expenditure	€	0	0	6816000	6816000	109056000	109056000	218112000	218112000	218112000	340800000	
Interest	€	0	0	409012	409012	6544186	6544186	13088372	13088372	13088372	20450581	
Operating Cost	€	0	0	3677012	3677012	58832186	58832186	117664372	117664372	117664372	183850581	
Annual Revenue	€	0	0	4727014	4727014	75632227	75632227	151264455	151264455	151264455	236350711	
Annual Net Cash Flow 7c per kWh gas and 5c per kwh heat	€	0	0	1050003	1050003	16800042	16800041	33600083	33600083	33600083	52500130	
Discount Rate	Percentage	0	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Years	years	0	0	15	15	15	15	15	15	15	15	
NPV	€	0	0	€1,057,763	€1,057,763	€16,923,472	€16,923,472	€33,846,894	€33,846,894	€33,846,894	€52,885,745	-€26,178,468
GHG abated (ktonne)	kt CO_2e yr^{-1}	0	0	5.33	5.33	85.25	85.25	170.50	170.50	170.50	266.40	131.87
Abatement Cost	€ t^{-1} CO_2e	0	0	-€198.53	-€198.53	-€198.52	-€198.52	-€198.52	-€198.52	-€198.52	-€198.52	-€198.52
Pathway 2	Units			20800	104000	312000	832000	1664000	2704000	4368000	5200000	
Low Cost		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
No of Plants				1	4	10	25	40	50	60	60	
Cumulative No. of Plants				1	5	15	40	80	130	210	285	
Gas Energy	Gwh	0	0	20	100	300	800	1600	2600	4200	5700	
Volume Methane	m^3	0	0	1895734	9478673	28436019	75829384	151658768	246445498	398104265	540284360	
Capital Expenditure	€	0	0	€5,816,000	€29,080,000	€87,240,000	€232,640,000	€465,280,000	€756,080,000	€1,221,360,000	€1,657,560,000	
Interest	€	0	0	€262,031	€1,310,154	€3,930,461	€10,481,228	€20,962,456	€34,063,992	€55,026,448	€74,678,751	
Operating Cost	€	0	0	-€2,330,031	-€11,650,154	-€34,950,461	-€93,201,228	-€186,402,456	-€302,903,992	-€489,306,448	-€664,058,751	
Annual Revenue	€	0	0	€2,753,081	€13,765,403	€41,296,209	€110,123,223	€220,246,445	€357,900,474	€578,146,919	€784,627,962	
Annual Net Cash Flow 7c per kWh gas and 5c per kwh heat	€	0	0	€423,050	€2,115,249	€6,345,748	€16,921,995	€33,843,989	€54,996,482	€88,840,472	€120,569,211	

Discount Rate	Percentage	0	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Years	years	0	0	€15	€15	€15	€15	€15	€15	€15	€15	
NPV	€	0	0	-€2,643,603	-€13,218,013	-€39,654,731	-€105,744,108	-€211,492,114	-€343,668,350	-€555,166,879	-€753,440,781	-253128572
GHG abated (ktonne)	kt CO_2e yr^{-1}	0	0	5.33	26.64	79.92	213.12	426.24	692.64	1,118.88	1,518.48	510.16
euro per tonne abated	€ t-1 CO_2e	0	0	€496.17	€496.17	€496.17	€496.17	€496.17	€496.17	€496.17	€496.17	-496.17
				14000	70000	210000	560000	1120000	1820000	2940000	3500000	
Pathway 2	Units			20800	104000	312000	832000	1664000	2704000	4368000	5200000	
High Cost		2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
No of Plants		0	0	1	4	5	30	40	50	80	75	
Cumulative No. of Plants		0	0	1	5	10	40	80	130	210	285	
Volume Methane	m^3	0	0	1895735	9478673	28436019	75829384	151658768	246445498	398104265	540284360	
Gas Energy	Gwh	0	0	20	100	300	800	1600	2600	4200	5700	
Capital Expenditure	€	0	0	-€6,816,000	-€34,080,000	-€102,240,000	-€4,089,600,000	-€545,280,000	-€886,080,000	- €1,431,360,000	-€1,942,560,000	
Interest	€	0	0	€409,012	€2,045,058	€6,135,174	€16,360,465	€32,720,930	€53,171,511	€85,892,440	€116,568,312	
Operating Cost	€	0	0	-€3,677,012	-€18,385,058	-€55,155,174	-€147,080,465	-€294,160,930	-€478,011,511	-€772,172,440	-€1,047,948,312	
Annual Revenue	€	0	0	€4,727,014	€23,635,071	€70,905,213	€189,080,569	€378,161,137	€614,511,848	€992,672,986	€1,347,199,052	
Annual Net Cash Flow 7c per kWh gas and 5c per kwh heat	€	0	0	€1,050,003	€5,250,013	€15,750,039	€42,000,104	€84,000,208	€136,500,338	€220,500,545	€299,250,740	
Discount Rate	Percentage	0	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Years	years	0	0	15	15	15	15	15	15	15	15	
NPV	€	0	0	€1,057,763	€5,288,816	€15,865,758	€42,310,530	€84,617,162	€137,509,223	€222,119,969	€301,448,512	€125,021,833
GHG abated (ktonne)	kt CO_2e yr^{-1}	0	0	5.328	26.64	79.92	213.12	426.24	692.64	1118.88	1518.48	629.7696
Abatement Cost	€ t^{-1} CO_2e	0	0	-€198.53	-€198.53	-€198.52	-€198.53	-€198.52	-€198.53	-€198.52	-€198.52	-€198.52

Table A1.26: Overview of Modelling Assumptions Used and Results for Wood Energy

	Woodchip etc	**Heat**		**Electricity**										
	tCO2e per GwH	**327.93**	**heat**	**467.6**	**electricity**	**from EPA**								
			2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
	Forestry thinings	000 m^3	491	725	959	1193	1427	1661	1653	1645	1637	1629	1621	1331.0
	Sawmill residues		142	145.6	149.2	152.8	156.4	160	164.2	168.4	172.6	176.8	181	160.8
	Forestry thinings	ktoe	51.975	76.131	100.287	124.443	148.599	172.755	172.194	171.633	171.072	170.511	169.95	139.1
	Sawmill residues		142	145.6	149.2	152.8	156.4	160	164.2	168.4	172.6	176.8	181	160.8
	Forestry thinings	GWh	604.5	885.4	1166.3	1447.3	1728.2	2009.1	2002.6	1996.1	1989.6	1983.0	1976.5	1617.2
	Sawmill residues		1651.5	1693.3	1735.2	1777.1	1818.9	1860.8	1909.6	1958.5	2007.3	2056.2	2105.0	1870.3
	Forestry thinings	$ktCO_2e\ yr^{-1}$	224.0	328.1	432.2	536.3	640.5	744.6	742.1	739.7	737.3	734.9	732.5	599.3
	Sawmill residues	$ktCO_2e\ yr^{-1}$	612.0	627.5	643.0	658.6	674.1	689.6	707.7	725.8	743.9	762.0	780.1	693.1
	Total GHG reductions	**$ktCO_2e\ yr^{-1}$**	**836.0**	**955.7**	**1075.3**	**1194.9**	**1314.5**	**1434.2**	**1449.8**	**1465.5**	**1481.2**	**1496.9**	**1512.6**	**1292.4**
Income	Forestry thinings	€ yr^{-1}	€11,047,500	€16,312,500	€21,577,500	€26,842,500	€32,107,500	€37,372,500	€37,192,500	€37,012,500	€36,832,500	€36,652,500	€36,472,500	€29,947,500
	Sawmill residues	€ yr^{-1}	€3,195,000	€3,276,000	€3,357,000	€3,438,000	€3,519,000	€3,600,000	€3,694,500	€3,789,000	€3,883,500	€3,978,000	€4,072,500	€3,618,409
Harvest & Transport (€19 per m3)	Forestry thinings	€ yr^{-1}	€9,329,000	€13,775,000	€18,221,000	€22,667,000	€27,113,000	€31,559,000	€31,407,000	€31,255,000	€31,103,000	€30,951,000	€30,799,000	€25,289,000
	Sawmill residues	**€ yr^{-1}**	**€2,698,000**	**€2,766,400**	**€2,834,800**	**€2,903,200**	**€2,971,600**	**€3,040,000**	**€3,119,800**	**€3,199,600**	**€3,279,400**	**€3,359,200**	**€3,439,000**	**€3,055,545**
Net Income	**Forestry thinings**	**€ yr^{-1}**	**€7,852,500**	**€13,036,500**	**€18,220,500**	**€23,404,500**	**€28,588,500**	**€33,772,500**	**€33,498,000**	**€33,223,500**	**€32,949,000**	**€32,674,500**	**€32,400,000**	**€26,329,091**
	Sawmill residues	**€ yr^{-1}**	**€497,000**	**€509,600**	**€522,200**	**€534,800**	**€547,400**	**€560,000**	**€574,700**	**€589,400**	**€604,100**	**€618,800**	**€633,500**	**€562,864**
	Total income	**€ yr^{-1}**	**€17,181,500**	**€26,811,500**	**€36,441,500**	**€46,071,500**	**€55,701,500**	**€65,331,500**	**€64,905,000**	**€64,478,500**	**€64,052,000**	**€63,625,500**	**€63,199,000**	**€51,618,091**

	Abatement Cost	**€ t^{-1} CO_2e**	**-€20.55**	**-€28.06**	**-€33.89**	**-€38.56**	**-€42.37**	**-€45.55**	**-€44.77**	**-€44.00**	**-€43.24**	**-€42.50**	**-€41.78**	**-€38.66**

Table A1.27: Overview of Modelling Assumptions Used and Results for Biomass Production

		Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Mean
	Area for heat	ha	0	0	2000	3000	4000	6000	9000	12000	14000	16000	6600
	Area for electricity	ha	0	0	200	500	1000	2000	3000	5000	7000	9000	2770
	heat GHG displaced	kt CO_2e yr^{-1}	0	0	21.4	32.1	42.8	64.2	96.4	128.5	149.9	171.3	70.7
	electricity GHG displaced	kt CO_2e yr^{-1}	0	0	3.7	9.3	18.7	37.4	56.0	93.4	130.7	168.1	51.7
Low Cost	Solid biomass for heat Net Cost	€ yr^{-1}	0	0	-428280	-642420	-856560	-1284840	-1927260	-2569680	-2997960	-3426240	-1413324
	Solid biomass for electricity Net Cost	€ yr^{-1}	0	0	-37353	-93382	-186763	-373527	-560290	-933817	-1307343	-1680870	-517334
	Abatement Cost (heat)	€ t^{-1} CO_2e	0	0	-20	-20	-20	-20	-20	-20	-20	-20	-16
	Abatement Cost (electricity)	€ t^{-1} CO_2e	0	0	-10	-10	-10	-10	-10	-10	-10	-10	-8
High Cost	Solid biomass for heat Net Cost	€ yr^{-1}	0	0	-963630	-642420	-856560	-1284840	-1927260	-2569680	-2997960	-3426240	-1466859
	Solid biomass for electricity Net Cost	€ yr^{-1}	0	0	-104587	-93382	-186763	-373527	-560290	-933817	-1307343	-1680870	-524058
	Abatement Cost (heat)	€ t^{-1} CO_2e	0	0	-45	-45	-45	-45	-45	-45	-45	-45	-36
	Abatement Cost (electricity)	€ t^{-1} CO_2e	0	0	-28	-28	-28	-28	-28	-28	-28	-28	-22.4

Table A1.28: Overview of Modelling Assumptions Used and Results for On-Farm Energy Efficiency

GHG reduction per unit	**Unit**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Mean**
Plate Cooler	$tCO_2e\ yr^{-1}$	0.69	1.39	2.08	2.78	3.47	4.16	4.86	5.55	6.25	6.94	3.82
VSD	$tCO_2e\ yr^{-1}$	0.23	0.46	0.7	0.93	1.16	1.39	1.62	1.86	2.09	2.32	1.28
Heat recovery	$tCO_2e\ yr^{-1}$	0.16	0.31	0.47	0.62	0.78	0.93	1.09	1.24	1.4	1.55	0.85
Solar PV	$tCO_2e\ yr^{-1}$	0.52	1.04	1.56	2.08	2.6	3.12	3.64	4.16	4.68	5.2	2.86
Net Cost @ annual electricity cost 20c kWh												
Plate cooler	€ unit-1 yr^{-1}	2500	1666.7	555.7	0	-833	-1666	-2499	-3332	-4165	-4998	
VSD	€ unit-1 yr^{-1}	3000	2727.3	2454.5	2181.8	1909.1	1636.4	1363.6	1090.9	818.2	545.5	
Heat recovery	€ unit-1 yr^{-1}	6000	5802	5604	5406	5208	5010	4812	4614	4416	4218	
Solar PV	€ unit-1 yr^{-1}	6000	5400	4800	4200	3600	3000	2400	1800	1200	600	
Uptake (no. farms)												
Plate cooler	farms	782	1564	2346	3128	3910	4692	5474	6256	7038	7819	
VSD	farms	391	782	1173	1564	1955	2346	2737	3128	3519	3909.5	
Heat recovery	farms	195.5	391	586.5	782	977.5	1173	1368.5	1564	1759.5	1954.75	
Solar PV	farms	195.5	391	586.5	782	977.5	1173	1368.5	1564	1759.5	1954.75	
GHG saving												
Plate Cooler	$tCO_2e\ yr^{-1}$	542.71	2170.83	4884.37	8683.33	13567.7	19537.49	26592.69	34733.31	43959.35	54263.86	20893.56
VSD	$tCO_2e\ yr^{-1}$	90.71	362.85	816.41	1451.39	2267.8	3265.63	4444.89	5805.57	7347.67	9070.04	3492.3
Heat recovery	$tCO_2e\ yr^{-1}$	30.3	121.21	272.72	484.84	757.56	1090.89	1484.82	1939.36	2454.5	3029.86	1166.61
Solar PV	$tCO_2e\ yr^{-1}$	101.66	406.64	914.94	1626.56	2541.5	3659.76	4981.34	6506.24	8234.46	10164.7	3913.78
Total	**$ktCO_2e\ yr^{-1}$**	**0.77**	**3.06**	**6.89**	**12.25**	**19.13**	**27.55**	**37.5**	**48.98**	**62**	**76.53**	**29.47**
Total Cost per year												
Plate cooler	€ yr^{-1}	1955000	2606667	1303594	0	-3257030	-7816872	-13679526	-20844992	-29313270	-39079362	-10812579
VSD	€ yr^{-1}	1173000	2132727	2879182	3412364	3732273	3838909	3732273	3412364	2879182	2132455	2932473
Heat recovery	€ yr^{-1}	1173000	2268582	3286746	4227492	5090820	5876730	6585222	7216296	7769952	8245135.5	5173998

Solar PV	€ yr^{-1}	1173000	2111400	2815200	3284400	3519000	3519000	3284400	2815200	2111400	1172850	2580585
Total	€ yr^{-1}	**€5,474,000**	**€9,119,376**	**€10,284,722**	**€10,924,256**	**€9,085,063**	**€5,417,767**	**-€77,631**	**-€7,401,132**	**-€16,552,736**	**-€27,528,922**	**-€125,524**
Abatement Cost	€ **tCO_2e**	**€7,152.00**	**€2,978.70**	**€1,493.00**	**€892.10**	**€474.80**	**€196.60**	**-€2.10**	**-€151.10**	**-€267.00**	**-€359.70**	**€1,240.70**
Net Cost @ annual electricity cost 40c kWh												
Plate cooler	€ unit-1 yr^{-1}	2500	-1666.7	-1778.1	-3444.1	-5110.1	-6776.1	-8442.1	-10108.1	-11774.1	-13440.1	
VSD	€ unit-1 yr^{-1}	3000	2454.5	1909	1363.5	818	272.5	-273	-818.5	-1364	-1909.5	
Heat recovery	€ unit-1 yr^{-1}	6000	5604	5208	4812	4416	4020	3624	3228	2832	2436	
Solar PV	€ unit-1 yr^{-1}	6000	4800	3600	2400	1200	0	-1200	-2400	-3600	-4800	
Cost												
Plate cooler	€ yr^{-1}	1955000	-2606719	-4171423	-10773145	-19980491	-31793461	-46212055	-63236274	-82866116	-105088142	-36477283
VSD	€ yr^{-1}	1173000	1919419	2239257	2132514	1599190	639285	-747201	-2560268	-4799916	-7465190.25	-586991
Heat recovery	€ yr^{-1}	1173000	2191164	3054492	3762984	4316640	4715460	4959444	5048592	4982904	4761771	3896645
Solar PV	€ yr^{-1}	1173000	1876800	2111400	1876800	1173000	0	-1642200	-3753600	-6334200	-9382800	-1290180
Total	€ yr^{-1}	**€5,474,000**	**€3,380,664**	**€3,233,726**	**-€3,000,847**	**-€12,891,661**	**-€26,438,716**	**-€43,642,012**	**-€64,501,550**	**-€89,017,328**	**-€117,174,361**	**-€34,457,808**
Abatement Cost	€ **tCO_2e**	**€7,152.00**	**€1,104.20**	**€469.40**	**-€245.00**	**-€673.70**	**-€959.50**	**-€1,163.70**	**-€1,316.80**	**-€1,435.90**	**-€1,531.10**	**€140.00**

Appendix 2. Details of Forestry Scenarios

Table A2.1: *Afforestation scenarios*

		Gg CO_2 eq. emissions/removals		
	Area (ha)	No future afforestation	Climate change plan targets	Additional removals
2021	2016	-2641.3	-2641.3	0.0
2022	4016	-2458.0	-2458.0	0.0
2023	8016	-2037.3	-2035.7	1.6
2024	12016	-1939.0	-1942.5	-3.5
2025	16016	-1997.3	-2015.6	-18.3
2026	24016	-1325.6	-1367.2	-41.6
2027	32016	-1139.2	-1218.0	-78.9
2028	40016	-954.7	-1087.1	-132.3
2029	48016	-739.0	-941.0	-202.0
2030	56016	-498.8	-785.4	-286.6
2031	60016	201.6	-181.0	-382.6
2032	64016	-357.5	-853.5	-496.0
2033	68016	-646.5	-1255.2	-608.7
2034	72016	-48.7	-774.2	-725.5
2035	76016	-285.6	-1131.3	-845.7
2036	80016	-21.1	-988.6	-967.5
2037	84016	-223.5	-1307.7	-1084.2
2038	88016	-284.0	-1467.8	-1183.8
2039	92016	-113.8	-1402.0	-1288.2
2040	96016	77.6	-1290.5	-1368.1
2041	100016	44.6	-1400.0	-1444.6
2042	104016	35.6	-1449.0	-1484.6
2043	108016	121.1	-1411.2	-1532.2
2044	112016	164.8	-1418.9	-1583.7
2045	116016	244.6	-1361.3	-1605.9
2046	120016	263.2	-1382.3	-1645.5
2047	124016	320.0	-1329.7	-1649.7
2048	128016	370.7	-1340.5	-1711.2
2049	132016	382.1	-1313.1	-1695.2
2050	136016	470.8	-1270.9	-1741.7

Table A2.2: *Extended rotation age*

	Gg CO_2 eq. emissions/removals		
	BAU	Ex Rot	emissions/removal difference
2021	590.2	531.2	-59.0
2022	988.1	973.3	-14.8
2023	1122.7	1103.6	-19.1
2024	1987.7	1610.4	-377.2
2025	2102.4	1535.7	-566.7
2026	2147.7	1493.5	-654.2
2027	1885.4	1079.4	-806.0
2028	1965.5	1200.1	-765.4
2029	2044.5	1206.5	-838.0
2030	1870.6	1491.7	-378.8
2031	2634.2	2558.6	-75.6
2032	2939.9	3227.9	287.9
2033	2536.1	2788.0	251.9
2034	3463.5	3957.9	494.4
2035	3293.9	3870.8	576.9
2036	3491.5	3831.1	339.6
2037	4042.4	4437.0	394.6
2038	3373.0	4054.6	681.6
2039	2984.5	3507.5	523.0
2040	2244.5	3151.2	906.7
2041	2178.1	2344.8	166.8
2042	2135.9	2389.7	253.9
2043	2025.4	2127.8	102.3
2044	1909.5	1923.8	14.3
2045	1901.6	1631.5	-270.1
2046	2151.9	1927.8	-224.1
2047	1979.1	1814.5	-164.7
2048	2174.4	1937.3	-237.1
2049	2174.3	2276.8	102.5
2050	2251.5	2379.0	127.5

Table A2.3: *Woodland conversion to birch on raised bogs*

	Gg CO_2 eq. emissions/removals		
	BAU	BL conversion	emissions/removal difference
2021	590.2	590.2	0.0
2022	988.1	988.1	0.0
2023	1122.7	1084.3	-38.4
2024	1987.7	1962.5	-25.2
2025	2102.4	2078.2	-24.2
2026	2147.7	2138.2	-9.5
2027	1885.4	1831.1	-54.2
2028	1965.5	1934.9	-30.6
2029	2044.5	2028.0	-16.5
2030	1870.6	1872.6	2.0
2031	2634.2	2607.6	-26.6
2032	2939.9	2890.2	-49.7
2033	2536.1	2518.1	-18.0
2034	3463.5	3440.7	-22.8
2035	3293.9	3266.6	-27.3
2036	3491.5	3416.4	-75.1
2037	4042.4	3980.1	-62.3
2038	3373.0	3297.2	-75.8
2039	2984.5	2898.3	-86.2
2040	2244.5	2047.3	-197.3
2041	2178.1	1783.8	-394.3
2042	2135.9	1760.1	-375.7
2043	2025.4	1612.9	-412.6
2044	1909.5	1550.3	-359.2
2045	1901.6	1539.9	-361.7
2046	2151.9	1743.3	-408.6
2047	1979.1	1652.9	-326.2
2048	2174.4	1729.3	-445.1
2049	2174.3	1520.6	-653.8
2050	2251.5	1475.0	-776.5

Table A2.4: *Agroforestry scenario*

		Gg CO_2 eq. emissions/removals		
	Area (Ha)	BAU	Agroforestry	Additional removals
2021	0	0.0	0.0	0.0
2022	0	0.0	0.0	0.0
2023	125	0.0	-0.2	-0.2
2024	250	0.0	-0.5	-0.5
2025	375	0.0	-1.0	-1.0
2026	500	0.0	-1.9	-1.9
2027	625	0.0	-3.1	-3.1
2028	750	0.0	-4.3	-4.3
2029	875	0.0	-5.8	-5.8
2030	1000	0.0	-7.4	-7.4
2031	1250	0.0	-8.6	-8.6
2032	1500	0.0	-9.9	-9.9
2033	1750	0.0	-11.5	-11.5
2034	2000	0.0	-13.7	-13.7
2035	2250	0.0	-16.3	-16.3
2036	2500	0.0	-19.0	-19.0
2037	2750	0.0	-22.0	-22.0
2038	3000	0.0	-24.1	-24.1
2039	3250	0.0	-24.7	-24.7
2040	3500	0.0	-25.8	-25.8
2041	4000	0.0	-28.2	-28.2
2042	4500	0.0	-31.7	-31.7
2043	5000	0.0	-35.0	-35.0
2044	5500	0.0	-39.7	-39.7
2045	6000	0.0	-44.6	-44.6
2046	6500	0.0	-49.1	-49.1
2047	7000	0.0	-51.0	-51.0
2048	7500	0.0	-54.4	-54.4
2049	8000	0.0	-57.1	-57.1
2050	8500	0.0	-61.4	-61.4