Modelling Irish Agricultural GHG Emissions and Mitigation to 2050:

Scenarios for the Carbon Budgets Working Group

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Context

This report outlines scenarios for agricultural Greenhouse Gas (GHG) emissions in Ireland using the FAPRI-Ireland model and Teagasc MACC model (2023) to assist the Climate Change Advisory Council (CCAC) in planning future carbon budgets. Ireland has committed to a 51% reduction in GHG emissions by 2030 and to achieving net climate neutrality by 2050. The Climate Action and Low Carbon Development Act (2021), set a national greenhouse gas (GHG) emissions reduction target and under the Act the Government allocated sectoral emissions ceilings and associated sectoral targets. Agriculture was set a 2030 target of reducing GHG emissions by 25% relative to 2018 emissions (Government of Ireland, 2022a). This is a highly ambitious target requiring high and rapid uptake of abatement options (Hanrahan et al. 2021).

Agricultural GHGs primarily come from methane (enteric fermentation and manure management), nitrous oxide (fertiliser and manure application), with carbon dioxide emissions also representing a more minor source.

The key factors influencing the level of agricultural GHG emissions in Ireland are:

- the level of economic activity in the sector and its composition
- the adoption of GHG mitigation measures

Agricultural GHGs in Ireland are mainly the result of bovine agriculture. The future level of GHGs from the sector is difficult to anticipate, reflecting uncertainties around the future size of the bovine population and the dairy-to-beef cow ratio, which affects the number of different type of bovines in the herd. Underlying this uncertainty regarding the level of economic activity in the agriculture sector and its composition, is fundamental uncertainty relating to the economic drivers of international agricultural input and output prices over a medium to long-term horizon. Further areas of uncertainty relate to future decisions relating to agricultural policy, trade policy and environmental policy, all of which are determined at supranational level. Added to these known uncertainties will be unanticipated events, so called unknown unknowns.

The projections to 2050 for agricultural activity levels in this report are conditional on the projected evolution of economic aggregates such as GDP per capita, inflation and the input and output prices to which farmers respond. It is important to emphasise that the projections under each of the three scenarios are not predictions or forecasts. The projections are based on a set of differing assumptions concerning future policy conditions that will affect bovine and general agriculture in Ireland. The fundamental uncertainty about the future evolution of these economic signals should be recognised when interpreting these projections and associated levels of GHG emissions.

The scenarios modelled using the FAPRI-Ireland model and the Teagasc GHG MACC summarised in this report do not provide model-based insights on the impact of agricultural activities on other environmental issues such as water quality and biodiversity, which both require spatially explicit modelling. It should be noted, however, that the measures to reduce nitrogen fertiliser use and change fertiliser type will have associated benefits in reducing nitrogen loss to water and ammonia loss to air. It is important to recall these modelling limitations when considering how the future adoption of mitigation technologies or agricultural activity levels may affect other indicators of interest.

Approach

The modelling work therefore has examined potential future GHG emissions under three agricultural activity scenarios (S1, S2, S3) with different levels of cow numbers, land use, and input usage, alongside two GHG mitigation pathways: P1 (ambitious adoption) and P2 (very ambitious adoption). The scenarios use the most up to date EPA National Inventory which reduced agricultural emissions in 2018 from 23.2 $MtCO_2e$ to 22.5 $MtCO_2e$ (EPA, 2024). Due to the uncertainties already set out, these scenarios **cannot be interpreted as predictions** of the future. The scenarios are elements in an exercise requested by the CCAC's Carbon Budget Working Group (CCWG) to help understand the scale of action that is likely to be required to mitigate future agricultural GHG emissions.

Scenario S1 (Base Case): In this scenario, by 2050 dairy cow numbers rise by 14%, increasing total milk production by 38% relative to 2022 due to higher milk yields. Total cattle inventories decrease by 7%, while beef production declines by 11%. Fertiliser use is projected to rise by 10%, and cropland area shrinks by 16% as grassland farming, especially dairying, becomes more profitable. Sheep numbers drop by 25%, while pig and poultry production grows by 25% and 30%, respectively.

Under scenario S1, Gross Value Added (a measure of income arising in the sector) is projected to grow in nominal terms, but the projected annual rate of growth over the period 2023-2050 is less than the projected rate of general inflation - in real terms sectoral incomes are projected to decline.

Scenario S2 (Lower Agricultural Activity): With reduced economic incentives for dairy and beef in this scenario, by 2050 total cattle inventories drop by 22% relative to 2022, driven by an 84% decline in beef cow numbers. Dairy cow numbers still rise by 7%, and with higher milk yields, milk production increases by 28%, but beef production falls 26% by 2050. Fertiliser use decreases by 12%, cropland contracts by 14%, and sheep numbers drop by 25%. Pig and poultry production grows by 25% and 35%.

Under scenario S2, with lower levels of agricultural activity, due to the projected strong contraction in the beef (suckler) cow herd, GVA in nominal terms is projected to grow but at a rate of only 0.9% per annum between 2023 and 2050. With general inflation of circa 2% per annum forecast, real sectoral income is projected to contract strongly under scenario S2.

Scenario S3 (Higher Agricultural Activity): Higher milk prices and support for beef farmers lead to a 22% increase in dairy cow numbers by 2050 relative to 2022 and a slower decline in beef cow numbers than in the other two scenarios. Total cattle inventories grow by 1%, milk production rises by 47% and beef production drops by less than 5%, a smaller decrease compared to S1 and S2. Fertiliser use rises by 22%, cropland area contracts by 24%, and sheep numbers decline by 25%. Pig and poultry production grow by 24% and 34%.

Under scenario S3, higher agricultural activity levels are associated with growth in GVA of slightly more than 2% for the period 2023 to 2050. With annual rates of price inflation of close to the same level forecast for the period to 2050 sectoral income real terms is projected to be grow marginally over the period to 2050.

In the absence of GHG mitigation, these three scenarios produce an agricultural GHG emissions range of 20.23 Mt CO_2e to 25.12 Mt CO_2e by 2050.

Mitigation Adoption Pathways: Two adoption pathways have been assessed:

- Pathway 1 (P1): An **ambitious** adoption rate following the 2023 Teagasc MACC.
- Pathway 2 (P2): **Very ambitious** adoption rates, with many measures extended close to the maximum potential rate to 2050.

Established practices like fertiliser formulation follow a linear adoption rate, while newer measures, such as feed additives, follow a more gradual adoption curve.

Results

Mitigation Results in Carbon Dioxide Equivalents to 2050:

- Adoption pathway P1 emissions were reduced to 17.52 Mt CO_2e (S1), 14.94 Mt CO_2e (S2), and 19.19 Mt CO_2e (S3), relative to a base level of 22.5 Mt CO_2e in 2018.
- Adoption pathway P2 delivered larger emission reductions, at 13.96 Mt CO_2e (S1), 11.75 Mt CO_2e (S2), and 15.38 Mt CO_2e (S3) relative to a base level of 22.5 Mt CO_2e in 2018.

The study indicates that only in scenarios where the highly ambitious (P2) pathway was adopted and agricultural activity remains stable (S1) or declines (S2), can Ireland be close to remaining within the 2021-2030 allocated agricultural sectoral emissions ceiling - equivalent to reducing agriculture emissions to 16.88 Mt CO_2e by 2030.

Mitigation Results in Carbon Dioxide Equivalents by 2050 relative to 2018:

- Scenario 1: emissions decrease by 22% (P1) and 38% (P2).
- Scenario 2: emissions decrease by 34% (P1) and 48% (P2).
- Scenario 3: emissions decrease by 15% (P1) and 32% (P2).

Mitigation Results by Individual Gases by 2050 relative to 2018:

- Scenario 1: Methane emissions decrease by 15% to 31% and nitrous oxide emissions drop by 55% to 72%.
- Scenario 2: Methane emissions decrease by 27% to 42%, while nitrous oxide emissions fall by 64% to 77%.
- Scenario 3: Methane emissions decrease by 7% to 24%, while nitrous oxide emissions fall by 49% to 68%.

Across all scenarios, nitrous oxide reductions are projected to occur primarily by 2030, while methane reductions are achieved more gradually over the period to 2050.

Key Takeaways for Policymakers

- **Significant Emission Reductions Require Very Ambitious Mitigation Efforts:** Achieving substantial reductions in agricultural GHG emissions by 2050 necessitates very ambitious adoption of mitigation measures (P2). High levels of uptake would allow the agriculture sector to contribute significantly to Ireland's national climate goals, including the 25% reduction target for agriculture by 2030 and further reductions by 2050, with potential reductions in agricultural emissions of between 38% and 48% by 2050 relative to 2018.

- **Agricultural Activity Levels Affect GHG Mitigation Potential:** Scenarios where agricultural activity is stable or reduced (S1 and S2) yield the largest GHG reductions relative to the 2018 level, particularly when coupled with very ambitious mitigation measures (P2). Scenario S3, which involves higher agricultural activity, achieves lower reductions in GHG emissions, highlighting the challenge of balancing agricultural productivity with emissions reduction.

- **Lower (higher) agricultural activity levels are associated with lower (higher) rates of growth in nominal agricultural sector income.** Under all scenarios modelled nominal GVA in agriculture (a measure of sectoral income) grows, but at rates that are projected to be less than expected rates of general inflation.

- **Lower (higher) agricultural activity levels across scenarios S1, S2 and S3 are reflected in lower (higher) levels of milk, beef and other agricultural output**. Across all scenarios modelled, beef production contracts and milk production expands. Developments in agricultural output levels will have consequences for output, employment and income arising in upstream and downstream industries.

- **Reducing Methane Emissions is Technologically Challenging:** While significant reductions in nitrous oxide emissions are feasible due to well-developed mitigation measures, reducing methane emissions poses greater technological challenges and is more costly. Methane mitigation technologies, like feed additives and manure management, are less efficacious compared to nitrous oxide mitigation and are slower to deploy. While feed additives are commercially available, they are utilised for housed bovines, principally fed on total mixed ration (TMR) diets. Deployment of feed additives during the grazing period is an immature technology at present with variable and highly uncertain results depending on the additive used.

- **Cumulative GHG Emissions Exceed Sectoral Ceilings without Very Ambitious Mitigation Measure Adoption:** Without very ambitious mitigation efforts (P2), agricultural emissions will likely exceed the sectoral emissions ceilings allocated for 2021–2030. This highlights the need for rapid and extensive implementation of GHG mitigation technologies.

- **No Single Measure Delivers a Substantial Share of the GHG Reductions:** A wide range of GHG mitigation measures contribute to reducing emissions, with no single measure providing a dominant share of the mitigation potential. Key contributors include reducing the age of cattle finishing, feed additives, fertiliser reformulation and improved breeding practices, like Dairy EBI.

- **Methane Reductions are Associated with Higher Costs:** Methane mitigation measures, particularly feed additives, are among the most costly, while some reduction measures, such as reducing the age of cattle finishing and Dairy EBI, result in considerable cost savings. It can be expected that economic considerations will play a significant role in determining the feasibility of achieving widespread methane mitigation and Government and industry support to farmers will be required to achieve very ambitious rates of adoption of mitigation measures.

- **Increased Carbon Dioxide Emissions Result from Certain Mitigation Measures:** Some mitigation strategies, such as liming and fertiliser reformulation, result in increased carbon dioxide emissions, partially offsetting reductions in other gases. This indicates the need for holistic consideration of trade-offs between emissions of different gases.

- **Achievement of Long-Term Agricultural GHG Reduction Targets will Require Consistent and Very Ambitious Mitigation Efforts:** If ambitious mitigation measures are continuously adopted, agricultural emissions could decrease by between 15% and 48% by 2050, depending on the combination of agricultural activity scenario (S1, S2, S3) and abatement adoption pathway (P1 or P2). The P2 abatement adoption pathway represents a degree of mitigation measure uptake that is at or near the maximum biophysical potential for a range of measures, including feed additives, fertiliser formulation and manure management options. Delivering such emission reductions would be a significant step towards achieving both the 2030 sectoral target and the 2050 goal of climate neutrality.

- **Policy and Incentives are Key to Achieving GHG Emissions Reductions**: There is a need to rapidly deploy the mitigation measures highlighted in the analysis. The very high rates of adoption for many measures, some with in excess of 70% uptake, can only be achieved through targeted policies and incentives. Advisory and extension services will guide farmers and landowners on the path to reduced GHG emissions by 2030 and to achieving further reductions in GHG emissions over the period to 2050.

- **Importance of Viable and Acceptable Farm Diversification Options:** In all of the mitigation scenarios modelled, the diversification measures were important contributors to reducing GHG emissions. Government and industry support for such alternative land uses will be critical in achieving the projected impact of these measures on agriculture sector GHG emissions.
- **Need for Continuing Research and Innovation**: There is a need for continuing research and development of emission mitigation technologies to identify new practices to reduce agricultural and land-use emissions. Research is also needed to further refine agricultural and land-use inventories to reduce uncertainty and provide inventory ready mitigation measures available for adoption by farmers.

2 Introduction

In this report, we set out agriculture sector GHG emissions scenarios analysed as part of the Teagasc contribution to the modelling work programme of the Carbon Budgets Working Group (CBWG) of the Climate Change Advisory Council (CCAC). The CBWG is tasked with developing an evidence base for the Council's carbon budget proposals, including the provision of modelling and analytical support. The modelling presented here is based on the FAPRI-Ireland model of the Irish agricultural economy and the Teagasc Marginal Abatement Cost Curve (MACC) published in July 2023 (Lanigan et al, 2023). Normally the FAPRI-Ireland and MACC work adopt a medium term (10-year time) horizon, but at the request of the CCAC, they have been extended to 2050. Extending the work over a 25 year horizon, creates a research question with an additional array of challenges and increases the uncertainty associated with any associated conclusions.

The Irish Government, under the Climate Action and Low Carbon Development Act 2021, and based on carbon budget proposals from the Climate Council, allocated sectoral emissions ceiling to agriculture and other sectors of the economy (Government of Ireland, 2022a). This sectoral emissions ceiling is equivalent to a 25% reduction in agricultural sectoral emissions by 2030 relative to 2018. The 2023 Teagasc MACC analysis sought to identify the most cost-effective pathway to reduce GHG emissions and enhance carbon sequestration in the agricultural, land-use, land use change and forestry (LULUCF) sectors plus (Bio) energy (Lanigan et al. 2023) in the context of the national climate objective and the allocated sectoral emissions ceilings. The research reported in this analysis extends the third iteration of the Teagasc GHG MACC (Lanigan et al., 2023) from 2030 to 2050 and is set in the context of exploring options for the Irish Government in achieving Net Climate Neutrality for Ireland by 2050.

In this updated analysis provided to the CBWG, the FAPRI-Ireland model of the Irish agricultural economy was modified to extend its projection horizon to 2050. Readers will note differences between projected levels of agricultural activity reported under these three scenarios to 2050 and those used in the 2020 Teagasc MACC (Lanigan et al., 2023). These differences reflect the extended model horizon and the updated macroeconomic and agricultural market outlook underlying these projections. The three potential agricultural activity scenarios modelled to 2050 using the FAPRI-Ireland model were:

- Scenario 1 (S1) a base case projection of agricultural activity levels;
- Scenario 2 (S2) a lower agricultural activity scenario, and
- Scenario 3 (S3) a higher activity scenario.

The Teagasc MACC (Lanigan et al., 2023) was also extended to 2050 to assess the impact of technical measures on agriculture emissions under each of these three alternative agricultural activity scenarios under two technology adoption pathways for the period to 2050.

- Pathway 1 (P1) ambitious technology adoption rates to 2050, similar to those evaluated for 2030 in Lanigan et al. (2023), are extended and analysed.
- Pathway 2 (P2) where very ambitious adoption rates are evaluated. These adoption rates further extend the ambition in Lanigan et al. (2023). The adoption rates for feed additives were further extended to almost all dairy cows, a large proportion of other cattle and 20% of sheep. There was also further reduction in the age of finishing. The increased adoption would be transformative for the sector.

Section 3 provides information on the projected evolution of agricultural activity levels and associated volumes of agricultural output produced for the period to 2050, based on the three projection scenarios.

Section 4 outlines the methods used to quantify the GHG emissions, mitigation and removals, reflecting the ambitious (P1) and the very ambitious (P2) mitigation technology adoption pathways.

Section 5 presents the results of the projected agricultural GHG emissions and mitigation potential under the different mitigation scenarios.

Section 6 presents the conclusions that can be drawn from the analysis and provides key takeaway messages for policy makers.

3 Agricultural Activity Scenario Projections

In this section, the three activity scenarios used in the analysis are described, including details relating to the projected level of activity under each scenario for key sources of agricultural GHG emissions in Ireland.

3.1 Activity Scenario Projections

The FAPRI-Ireland model was used to generate three alternative scenarios, which *exclude any mitigation* from additional measures. These three scenarios represent the Base case projection S1, the lower agricultural activity scenario S2 and the higher agricultural activity scenario S3. These scenarios were developed for sensitivity purposes in the reporting of GHG emissions under the Monitoring Mechanism Regulation. These scenarios reflect some of the uncertainty concerning future levels of agricultural activity in Ireland over the period to 2050.

It is important to emphasise that the projections under each of the three scenarios are not predictions or forecasts. The projections are based on a set of differing assumptions concerning future policy conditions that will affect bovine and general agriculture in Ireland. The activity and commodity projections are also conditional on the projections of future EU and World agricultural commodity market conditions and wider macroeconomic developments that are used in the model. The three different agricultural scenarios are presented as an aide to understanding a range of different future potential outcomes for agricultural activity levels and associated GHG emissions in the presence of policy and market uncertainty. The use of these agricultural activity scenarios in this analysis is primarily to explore:

- How much mitigation of GHG emissions is possible with the set of technologies and management practices available currently (Lanigan et al., 2023) and
- The influence of economic activity in the agricultural sector on emissions over the period to 2050.

3.2 Exogenous Agricultural and Macro Data in the Scenarios

The FAPRI-Ireland model takes projections of global and European agricultural commodity prices and agricultural input prices (such as feed and fertiliser) from colleagues at the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri. These projections of European and World agricultural commodity prices extend to 2035.

Since the FAPRI-Ireland model usually projects agricultural economic activity on a 10 year forward basis, projecting forward to 2050 significantly increases model uncertainties. FAPRI and other agencies that provide medium term projections of agricultural commodity and input prices do not provide projections to a 2050 horizon.

Projections of some required exogenous data were unavailable to 2050. Therefore, to extend the modelling horizon for the FAPRI-Ireland model to 2050 assumptions about the evolution of agricultural commodity output and input prices were necessary. The evolution of input and output prices was informed by projected energy and general inflationary developments provided by the ESRI for the period to 2050.

To simulate to a 2050 horizon is was necessary to make assumptions about how agricultural commodity prices might evolve over the period 2035-2050. In extending the simulation horizon to 2050 these prices are assumed to remain unchanged in nominal terms between 2035 and 2050.

FAPRI-Ireland projections of Irish fertiliser prices are driven by exogenous macroeconomic projections of natural gas and oil prices provided by the ESRI. The dramatic increase in fertiliser prices following the illegal

Russian invasion of Ukraine is projected to largely reverse over the period to 2026. Thereafter Irish fertiliser prices are projected to follow the projected development of global energy prices.

A summary of the macroeconomic projections for the period to 2050 are summarised in Table 1.

Table 1: Growth Rates (rate of change per annum) of key Macroeconomic variables 2024-2050.

	2024	2025-2030	2031-2050
	Percentage rate of change per annum		
Modified Domestic Demand	2.0%	3.9	2.5
Brent Oil Price (USD per barrel)	-1.2%	1.60%	1.30%
Gas Price (USD per barrel equivalent)		1.60%	1.30%
Personal Consumption Deflator	2.9%	3.40%	1.50%
	Currency exchange rates per euro		
US$	1.08	1.13	1.13
GB£	0.87	0.88	0.88

Source: ESRI (Personal Communication)

The macroeconomic aggregates taken from the ESRI COSMO model (personal Communication Paul Egan) and the international agricultural commodity and input prices taken from the FAPRI-EU model are unchanged across the three scenarios (S1, S2 and S3).

3.3 No Mitigation Business as Usual Projections

In all three agricultural activity scenarios (S1, S2 and S3) we have calculated a "business as usual" projection where none of the measures evaluated in the Teagasc MACC report are adopted by Irish farmers. This assumption is made to facilitate the evaluation of the impact of the MACC measures on agricultural GHG emissions, rather than as a forecast of the behaviour in aggregate of Irish farmers over the period to 2050.

Government, supported by State Agencies such as Teagasc, have developed Climate Action Plans with the objective of supporting the adoption of mitigation measures, such as those evaluated in the 2023 MACC report and in this report. Government and industry stakeholders have engaged, via Food Vision Groups, to address how GHG emissions associated with Irish agricultural activities can be reduced (Government of Ireland 2022b; Government of Ireland 2022c).

The key driver of agricultural GHG emissions in Ireland continues to be the level of activity in bovine agriculture. There is a degree of uncertainty as to how the bovine population will develop in Ireland over the next 25 years, both in terms of the number of animals and the relative share of dairy and beef cows in the herd. Therefore three agricultural activity scenarios have been produced (base case S1, lower agricultural activity scenario S2 and higher agricultural activity scenario S3) differing from one another in terms of dairy and beef (suckler) cow numbers, associated cattle progeny, land use and use of fertilisers and other inputs.

3.4 Scenario 1 - Base Case

The Base case projection (S1) is the FAPRI-Ireland base case projection, which is aligned with the FAPRI (September 2023) base case projections for medium term developments in EU and World agricultural commodity markets. Agricultural policy (and related agricultural trade and agri-environmental policies) is assumed to remain unchanged for the whole of the model's extended projection period to 2050. Under S1 (and similarly under S2 and S3) we assume that none of the GHG emissions mitigation measures considered in the Teagasc MACC are implemented over the period 2023-2050. Table 2 shows key projections under S1, while Figure 1 plots the evolution in the cattle population under S1.

Table 2: Base case level of agricultural activity (Scenario 1)

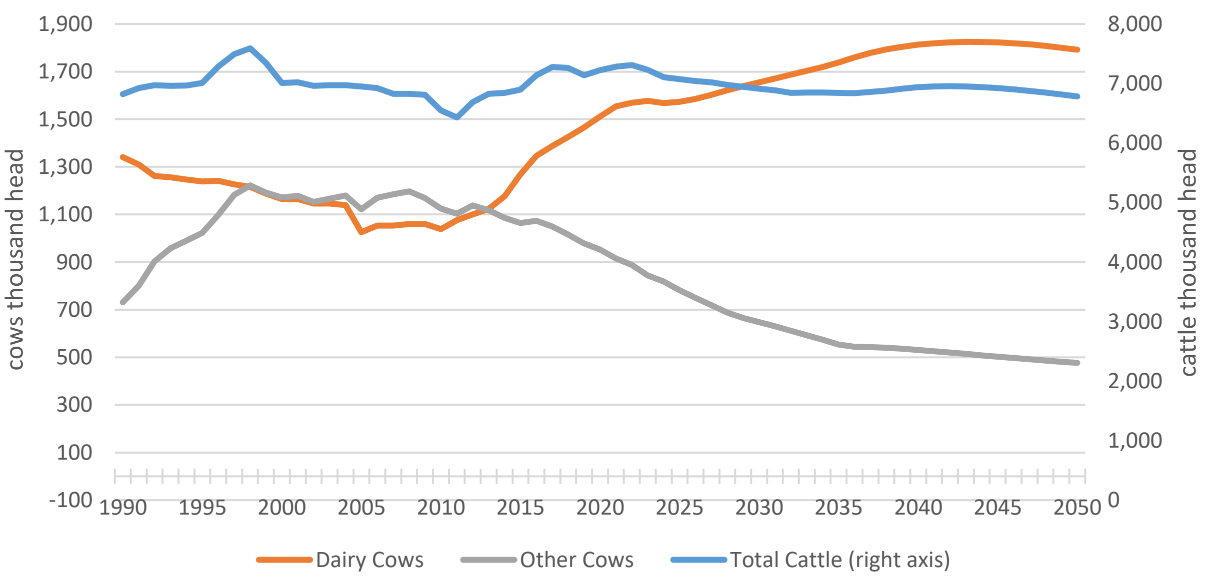
		2018	2022	2030	2040	2050
Dairy Cows	000 head	1,425	1,569	1,656	1,813	1,792
Beef (Suckler) Cows	000 head	1,015	887	648	531	477
Total Cattle	000 head	7,261	7,311	6,912	6,938	6,785
Total Cereal Area	000 ha	261	286	283	249	229
Total N Fertiliser	000 t	408	343	375	376	378
Milk production	000 t	8,133	9,442	10,433	12,346	13,003
Beef production	000 t cwe	623	621	581	577	555

Source: FAPRI-Ireland Model 2024

Under the base case (S1), dairy cow numbers are projected to increase up to the mid-2040s and then plateau over the remaining years of the projection period. The projected growth in the dairy cow herd under Scenario S1 (see Table 1) reflects the fact that dairy production is projected to remain profitable in Ireland. Dairy cow numbers in 2050 are projected to reach 1.792 m, having peaked at 1.825 m in 2043. This represents a 14% increase in the dairy cow population relative to 2022. The rate of growth of the Irish dairy cow herd over the whole of the projection period is far slower than that observed over the last decade, reflecting the increasing marginal costs of expanding the dairy cow herd over the projection period.

Due to projected growth in dairy cow numbers and expected improvements in the average volume of milk produced per cow (productivity improvements), total production of milk in Ireland and associated production of dairy commodities such as butter, cheese and milk powders increases. By 2050 total Irish milk production is projected to be 38% higher than in 2022, with roughly 60% of the projected growth arising from improvements in yields per cow and remainder from projected growth in dairy cow numbers.

Figure 1: Total Cattle, Dairy and Other Cow Inventories 1990-2050 (Base Case S1)



Source: Historical data EPA, Projections from 2024 FAPRI-Ireland Model.

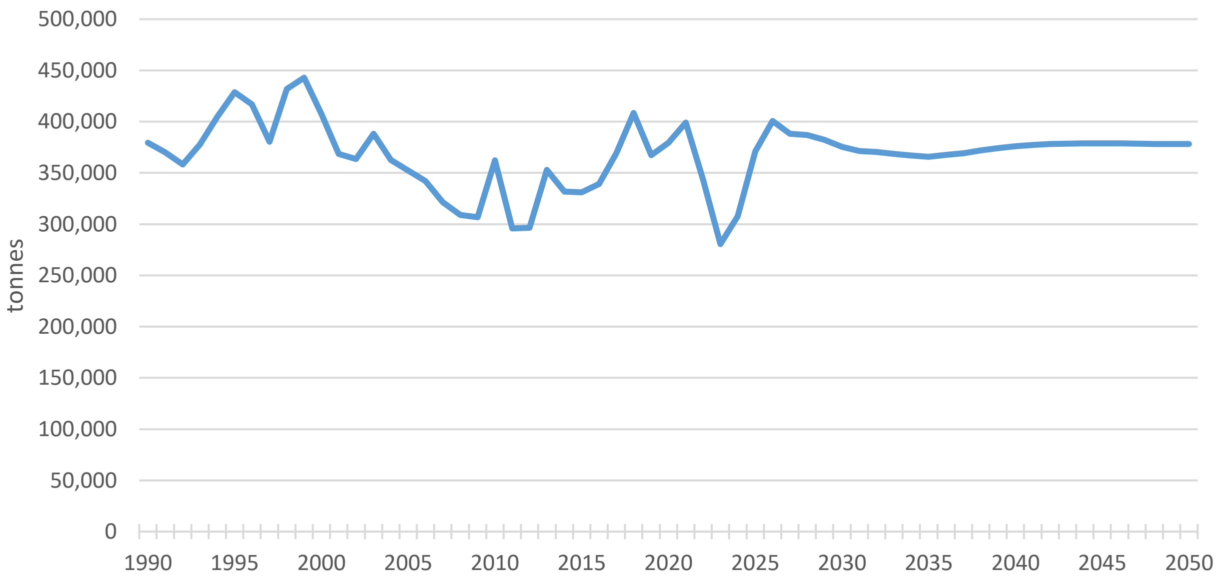
In contrast to projected developments in dairy cow inventories, the projected low levels of profitability of beef cow (suckler) based production systems is reflected in a continued contraction of beef cow inventories over the whole of the S1 projection period to 2050. Beef cow numbers in 2050 are projected to decline to 0.477 m under the S1 scenario. This represent a 46% decrease relative to 2022 (Table 1).

The projected future evolution of the overall cattle inventory is largely determined by developments in these two bovine 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 S1 are projected to decline over the period to 2050 (Table 1). By 2050, total cattle numbers are projected to be 7% lower than in 2022. Total cattle inventories in 2050 are projected to be 6.79 m. Reflecting the projected lower total cattle inventory and the increase in the share of cattle produced by dairy as opposed to beef cows (reflected in reduced average slaughter weight), total beef production (in carcass eight equivalent) in 2050 is projected to be close to 11% lower than in 2022.

While total cattle inventories are declining over the S1 projection period, growth in dairy cow numbers and the projected contraction in beef cow numbers will continue to change the composition of the Irish bovine inventory and the intensity of grassland use. Dairy production systems operate at a higher stocking rate than beef cow based production systems and this higher stocking rate is reflected in higher projected use of nitrogen fertiliser per hectare of grassland (on average dairy farms use roughly three times as much nitrogen per hectare relative to cattle farms). Total aggregate nitrogen fertiliser use in Irish agriculture is projected to be 378,201 tonnes by 2050. This represent a 10% increase relative to 2022 (Table 1). This projected increase in aggregate fertiliser use is clear from Figure 2 and is reflective of the very low levels of fertiliser use in 2022 when extremely high fertiliser prices, due to the Russian invasion of Ukraine led to large reductions in fertiliser use by Irish farmers. Under S1, fertiliser prices are projected to return to levels close to those prevailing prior to the Russian invasion of Ukraine and consequently fertiliser use is projected to increase towards levels of use observed prior to the war in Ukraine by 2026. While policy makers would like to see a permanent reduction in fertiliser use this is not reflected in S1 since it cannot be said with any certainty that it will occur. Instead, lower levels of fertiliser use are treated as a mitigation action.

Figure 2: Total Fertiliser Sales 1990-2050 (Base Case S1 with no mitigation (Business as Usual)).



Source: Historical data EPA, Projections from 2024 FAPRI-Ireland Model.

Under the Scenario S1, Irish ewe and total sheep numbers are projected to decline over the period to 2050 due to projected reductions in the real price of lamb. While nominal prices of lamb are projected to grow over the projection period, the rate of growth in nominal lamb prices is more than offset by the projected growth in the prices of inputs used in the production of lamb. By 2050, total Irish sheep numbers are projected to decline to 4.16 m. This represents a 25% decline relative to 2022.

Under Scenario S1, the total volume of pig output is projected to grow over the period to 2050. Breeding pig numbers as well as overall pig inventories are projected to grow over the period to 2050. Irish pig meat prices reflect developments in global and EU pig meat markets. Nominal Irish pig prices are projected to remains relatively stable at close to current prices for most of the projection period. Total breeding pig inventories in Ireland in 2050 are projected to be 13% higher than in 2022, with projected improvements in the number of pigs per sow (productivity growth), total pig inventories are projected to grow by 25% by 2050 as compared to 2022.

Under Scenario S1, Irish poultry production is projected to continue to grow over the projection period to 2050. Projected continued growth in per capita consumption of poultry underpins the continued growth in poultry production in Ireland. Nominal poultry prices are projected to remain stable over the period to 2050, with ongoing productivity growth is sufficient to support growth in volume that over the period to 2050 cumulates to an increase of over 30% in poultry output volume relative to 2022.

Under S1, the total crop land area is projected to contract due to the higher level of profit per hectare in grassland farming (dairying) as compared to tillage. By 2050, the total cereal area harvested in Ireland is projected to decrease to 229,280 hectares, representing a 16% decrease relative to 2022.

3.5 Scenario 2 - Lower Agricultural Activity Scenario

The S2 scenario is a projection of lower bovine activity than S1. In S2, Irish milk prices are assumed to be lower than under S1, while negative subsidies are introduced to the model to dis-incentivise the farming of beef (suckler) cows. These two assumptions are purposefully designed as modelling tools to reduce the economic incentives to farm both beef cows and dairy cows. As a result, the level of total cattle inventories and other related agricultural activities (e.g. fertiliser use) are much lower in S2 than in S1 scenario. These model assumptions do not represent recommendation for policy actions, nor are they forecasts of what the economic incentives faced by Irish cattle farmers will or should be over the period to 2050. Rather the S2 scenario is designed to illustrate the impact on agricultural GHG emission of levels of agricultural activity that are lower than in S1. As detailed later in section 4, S2 also allows the examination of the level of mitigation, which might be achievable with these lower levels of economic activity through the adoption of the mitigation measures specified in the Teagasc MACC (Lanigan et al., 2023). The lower levels of economic activity projected under S2 relative to S1 are reflected in lower GHG emissions from agriculture, but also lower levels of agricultural output value and value added (income) generated by the agricultural sector.

Under S2, despite the lower level of Irish milk prices assumed, Irish dairy cow numbers are still projected to increase 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 assumed under scenario S2. Dairy cow numbers in 2050, under S2, are projected to reach 1.673 m. This represents a 7% increase relative to 2022, a relatively modest change over a quarter of a century. However, the projected dairy cow herd inventory in S2 in 2050 represents a greater than 100,000 head decline relative to the projected inventory in S1 by 2050. Under the lower activity scenario S2, beef cow numbers in 2050 are projected to decline to 0.140m. Under S2, the rate of contraction in beef cow numbers is much more significant than under S1. The decline under S2 of 84% relative to 2022 leaves Irish suckler cow numbers at levels never previously recorded in Irish agricultural statistics. Given the spatial concentration of suckler cow farming activity in the Northern & Western Region, such a decline would represent an enormous shock to regional agricultural activity levels. Even though the total cattle population is falling under S2, the dairy share of this population is increasing and the higher stocking rate on dairy farms partially offsets declining stocking rates on beef farms.

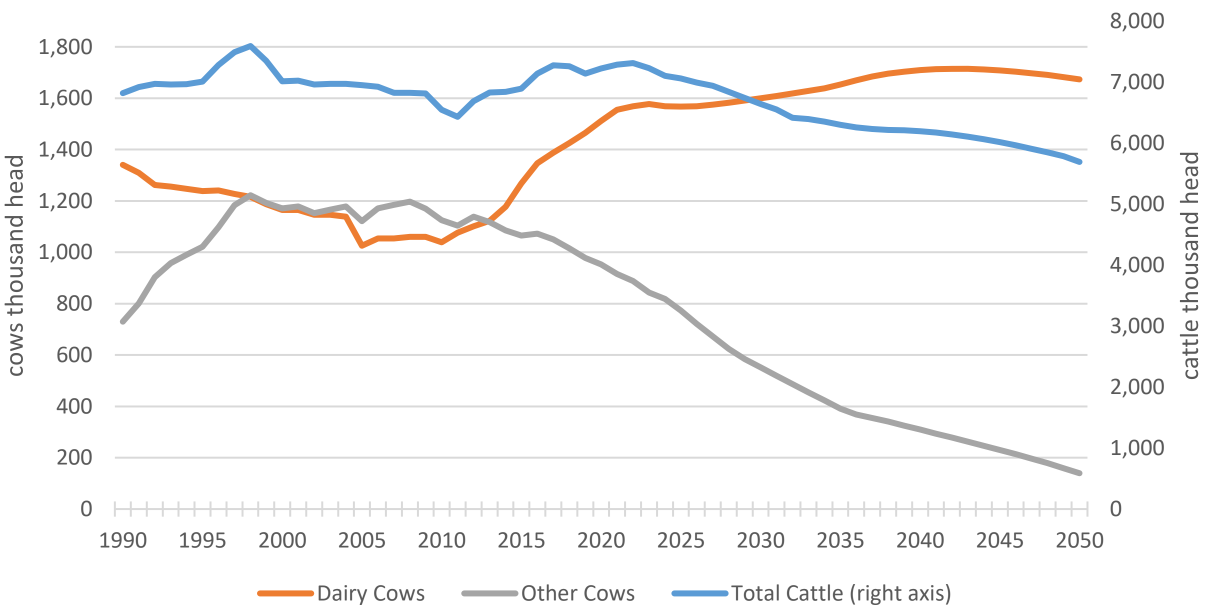
Table 3: Lower levels of agricultural activity (Scenario 2)

		2018	2022	2030	2040	2050
Dairy Cows	000 head	1,425	1,569	1,600	1,709	1,673
Beef (Suckler) Cows	000 head	1,015	887	552	310	140
Total Cattle	000 head	7,261	7,311	6,641	6,197	5,692
Total Cereal Area	000 ha	261	286	287	260	246
Total N Fertiliser	000 t	408	343	358	331	304
Milk Production	000 t	8,133	9,442	10,027	11,593	12,103
Beef production	000 t cwe	623	621	566	530	458

Source: FAPRI-Ireland Model 2024

Therefore, under scenario S2, total cattle inventories are projected to decline over the projection period. The impact of a much lower beef cow population in S2 is more than sufficient to offset the projected growth in dairy cow inventories. Total cattle inventories in 2050 under S2 are projected to be 5.692 m. This represent a 22% decrease relative to 2022. The lower cattle inventory under Scenario S2 is reflected in declining volumes of beef production. Under Scenario S2, the total volume of beef produced declines to 458 kt carcass weight equivalent, a 26% reduction by 2050 relative to production in 2022. With continued, but slower, growth in dairy cow numbers under S2, milk production is still projected to increase over the period to 2050, with total deliveries in 2050 projected to be 28% higher than in 2022.

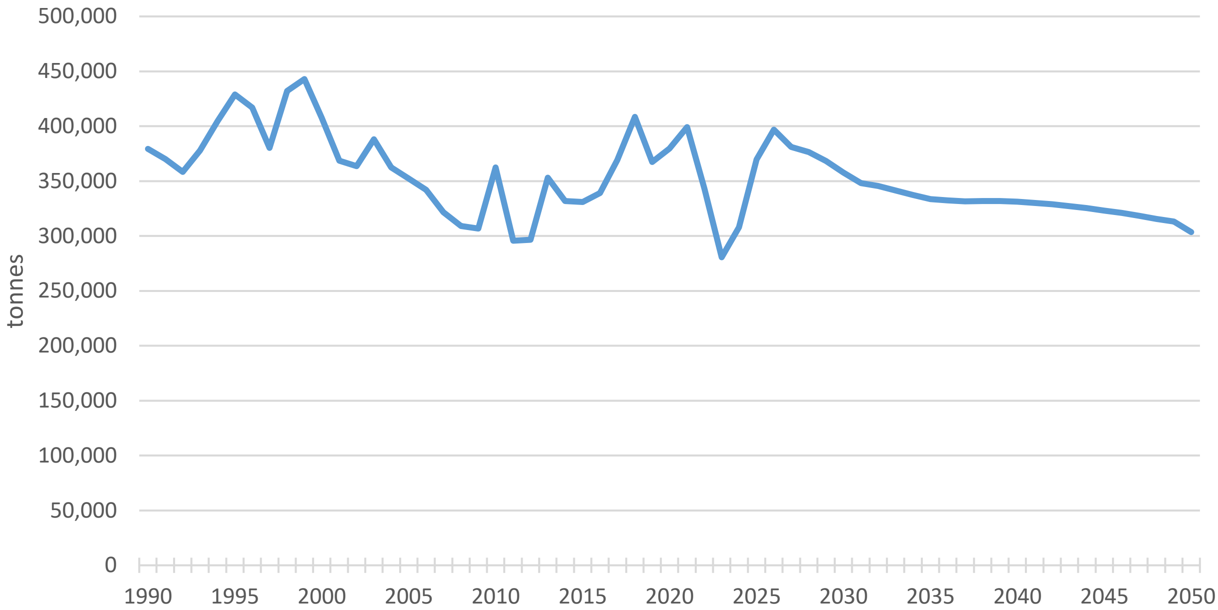
Figure 3: Total Cattle, Dairy and Other Cow Inventories 1990-2050 (Scenario S2)



Source: Historical data EPA, Projections from 2024 FAPRI-Ireland Model

Fertiliser use in the early years of the projection period recovers due to falling fertiliser prices, but over the period 2026 to 2050 lower agricultural activity levels, primarily the decline in the number of cattle, is reflected in declining aggregate fertiliser use. By 2050, the total use of Nitrogen is 303,582 tonnes. This represents a 12% decrease relative to the relatively low levels of fertiliser use in 2022. Total fertiliser use in 2050 under the S2 scenario is projected to be almost 20% lower than under S1 by 2050.

Figure 4: Total Fertiliser Sales 1990-2050 (Scenario S2 no mitigation Business as usual).



Source: Historical data EPA, Projections from FAPRI-Ireland Model 2024.

Under the S2 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 scenario S2 are projected to be approximately equal to those under S1, with breeding ewes and total sheep numbers both projected to decline. By 2050, sheep numbers are projected to decline to 4.16 m, a 25% decline on 2022 levels.

Projections for pig and poultry production under the lower agricultural activity scenario S2 are not different from those under S1. Neither pig nor poultry production activity in Ireland is a significant direct user of agricultural land. Irish pig and bird prices are largely determined by developments in EU and world markets. These factors mean that the changes in Irish bovine activity levels, which are the main feature of scenario S2, are not projected to lead to changes in the level of agricultural activity associated with pig and poultry production.

In scenario S2, total cropland is projected to contract at a slower rate than under scenario S1. The decline in the returns of both dairy and beef compared to tillage crops means that while the land area under crops declines, the rate of contractions is lower than under S1. By 2050, total cereal area harvested in Ireland declines to about 246,000 hectares. This represent a 14% decrease relative to 2022.

3.6 Scenario 3 - Higher Agricultural Activity Scenario

The future evolution of the Irish bovine inventory is uncertain. Heretofore, growth in the dairy cow inventory has been accompanied by contraction in the beef cow herd. The higher agricultural activity scenario S3 examines the consequences of a departure from this observed historical pattern, with continued strong growth in the dairy herd accompanied by a much slower projected contraction in the beef cow herd than has been observed since the end of the milk quota regime in 2015.

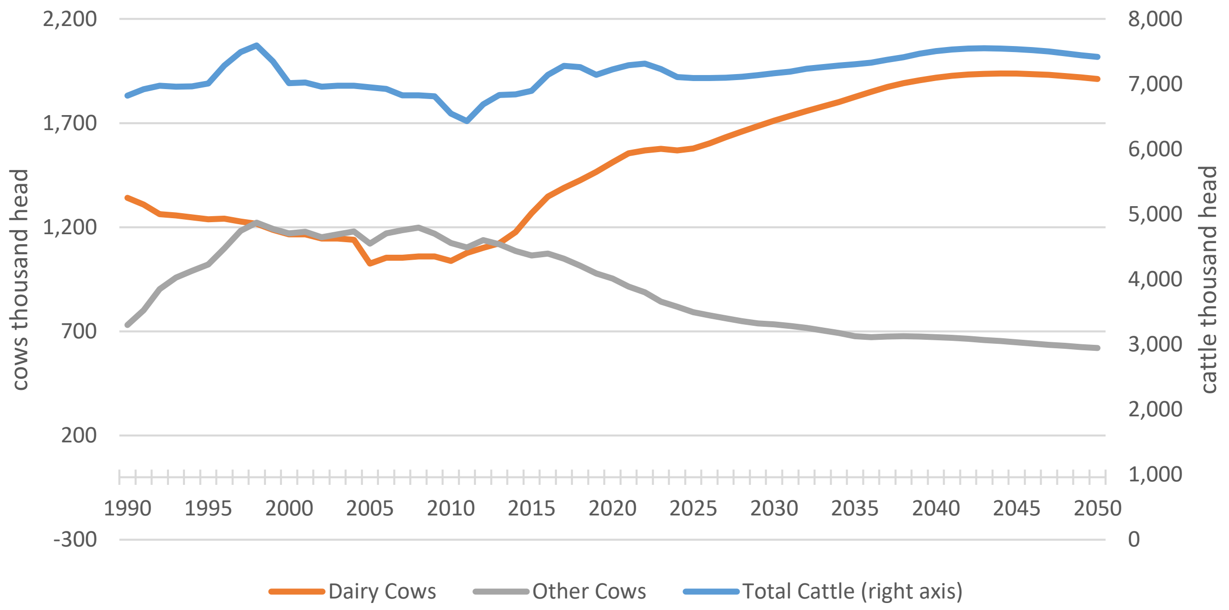
Table 4: Higher levels of agricultural activity (Scenario 3)

		2018	2022	2030	2040	2050
Dairy Cows	000 head	1,425	1,569	1,711	1,917	1,911
Beef (Suckler) Cows	000 head	1,015	887	734	673	620
Total Cattle	000 head	7,261	7,311	7,167	7,505	7,414
Total Cereal Area	000 ha	261	286	280	240	216
Total N Fertiliser	000 t	408	343	392	410	419
Milk production	000 t	8,133	9,442	10,841	13,103	13,907
Beef production	000 t cwe	623	621	594	610	593

Source: FAPRI-Ireland Model 2024

Under the scenario S3, from 2024 onwards additional coupled support is provided to beef cow (suckler) farmers. Irish farm gate milk prices are also assumed exogenously higher than under S1 by approximately 7%. These two assumptions about stronger economic incentives are used to generate a larger dairy and beef cow inventory than under scenario S1, to illustrate the impact of such a development on agriculture sector GHG emissions.

Figure 5: Total Cattle, Dairy and Other Cow Inventories 1990-2050 (Scenario S3)



Source: Historical data EPA, Projections from FAPRI-Ireland Model 2024.

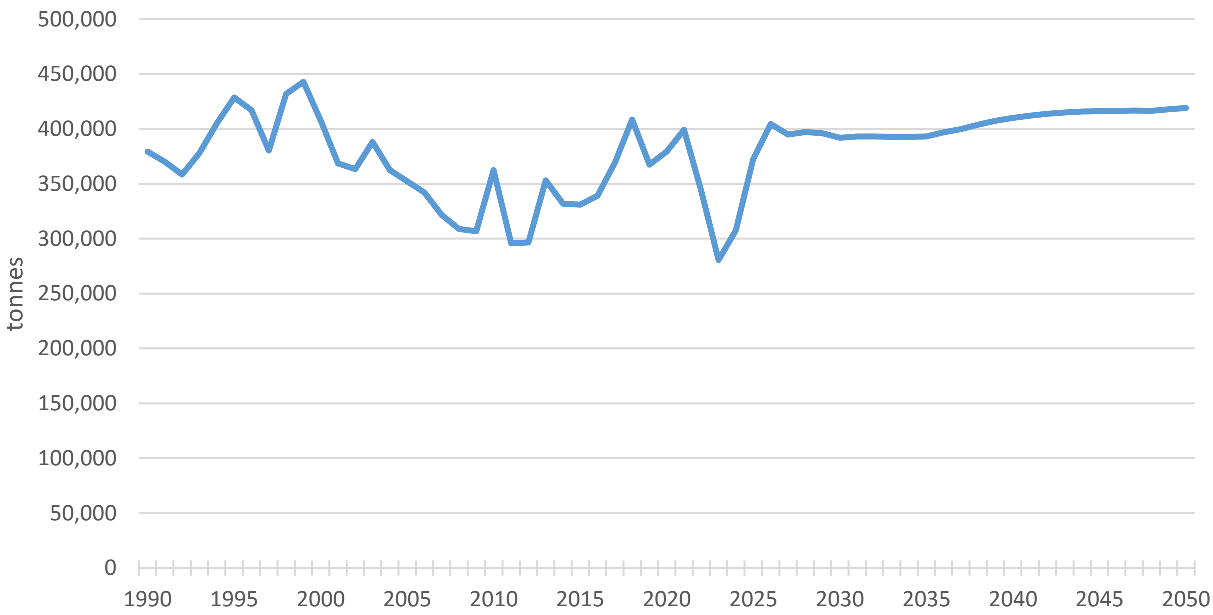
Under scenario S3, with stronger milk prices, Irish dairy cow numbers are projected to increase relative to the 2022 levels. Dairy cow numbers in 2050, under the higher agricultural activity scenario S3, are projected to reach 1.91 m. This represent a 22% increase relative to 2022. This represents a stronger increase relative to the inventory that is projected under scenario S1.

Under the higher agricultural activity scenario S3, the provision of coupled direct payments linked to suckler cows from 2024 onwards slows the projected rate of decline in the Irish beef cow inventory. By 2050, under scenario S3, Irish beef cow numbers are projected to be 0.620 m. This represents a 30% decrease relative to 2022. With higher agricultural activity levels in S3, the volumes of both beef and milk production are higher than under scenario S1. Milk production under S3 increases by 47% relative to the level in 2022, and while beef production decreases, the magnitude of the decline in beef production is much smaller than under both S1 and S2. By 2050 beef carcass production is projected to have declined by less than 5% compared to levels of beef produced in 2022.

Under scenario S3, aggregate cow inventories and total cattle inventories are projected to grow very marginally over the period to 2050. The increase in dairy cow inventories is offset by the still significant decrease in beef cow inventories that is projected. By 2050, projected total cattle inventories are 7.41 m. This represent a 1% increase relative to 2022.

Under scenario S3, the dairy share of the total cattle population increases and the higher stocking rate is reflected in a higher level of nitrogen use per hectare and in total nitrogen use in aggregate over the period to 2050. In 2050, the total use of nitrogen is projected to be 419,033 tonnes. This represent a 22% increase relative to the observed levels of use in 2050.

Figure 6: Total Fertiliser Sales 1990-2050 (High scenario S3 no mitigation Business as Usual).



Source: Historical data EPA, Projections from FAPRI-Ireland Model 2024.

Under the S3 scenario, lower economic returns to beef farming lead to further projected declines in beef cow inventories. While returns to sheep decline to beef, ewe and total sheep numbers under scenario S3 are projected to be approximately equal to those under S1, with breeding ewes and total sheep numbers both projected to decline. By 2050, sheep numbers are projected to decline to 4.16 m a 25% decline on 2022 levels.

Projections for pig and poultry production under the lower agricultural activity scenario S3 are not different from those under S1. Neither pig nor poultry production activity in Ireland is a significant direct user of agricultural land. 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 scenario S3 are not projected to lead to changes in the level of agricultural activity associated with pig and poultry production.

In scenario S3, total cropland area is projected to decrease over the period to 2030 at a higher rate than under either the S1 or S2. The higher profitability of land use in dairy production systems and beef production systems in scenario S3, leads to a faster movement of land from tillage to grassland use. By 2050, the total cereal area harvested in Ireland is projected to decrease to 216,250 hectares. This represents a 24% decrease relative to 2022.

3.7 Output, Input and Income under Agricultural Activity Scenarios S1, S2 and S3

The FAPRI-Ireland model is designed with a ten-year projection horizon in mind, meaning its structure and assumptions reflect factors that are likely to change over a ten-year horizon. Extending its application to a longer-term horizon (2050) introduces greater uncertainty and reduces its reliability. In the absence of projections to 2050 for key exogenous variables, extending the FAPRI-Ireland model's time horizon requires that assumptions are made about future evolution of output and input prices for the period 2035-2050. These assumptions are necessarily speculative and may not, ex post, reflect realised market dynamics, future policy changes or other factors that might influence future international production levels and output and input prices.

It has not been possible to assess how environmental policy constraints on agriculture might be applied internationally in the period to 2050. The environmental policy constraints which international agriculture could face could significantly alter market prices through shifts in production between countries and changes in global trade. Model assumptions about future prices may fail to accurately project the market consequences of such constraints. With these caveats in mind, the following assessment has been made of how output value and sectoral income might evolve over the period to 2050 under the three modelled activity scenarios.

Under each of the three agricultural activity scenarios modelled agricultural activity levels evolve over the period to 2050 in response to projected agricultural output and input prices and assumed policy incentives. Associated with these agricultural activity levels are volumes of agricultural output and volumes of inputs used and associated agricultural goods output values and values of expenditure on intermediate consumption and sectoral Gross Value Added (GVA).

Table 5: Agricultural Output, Input and Income under modelled agricultural activity scenarios

	2022	2023	S1 2050	S2 2050	S3 2050	S1	S2	S3
			Euro bn (current prices)			Annual Growth Rate 2023-2050		
Beef Output	3.03	3.01	2.56	2.10	2.76	-0.60%	-1.32%	-0.32%
Milk Output	5.01	3.51	6.74	5.85	7.69	2.45%	1.91%	2.95%
Other Agricultural Output	4.27	4.15	4.81	4.70	4.87	0.55%	0.46%	0.59%
Agricultural Output at Basic prices	12.92	11.30	14.76	13.30	15.97	0.99%	0.61%	1.29%
Intermediate Consumption	7.88	7.75	9.38	8.78	9.77	0.71%	0.46%	0.86%
GVA at Basic Prices	5.04	3.55	5.38	4.52	6.20	1.55%	0.90%	2.09%

Source: Historical data CSO, Projections from FAPRI-Ireland Model 2024.

The nominal value of cattle, milk and other agricultural output, intermediate consumption (input expenditure) and GVA under each of the three agricultural activity scenarios (S1, S2 and S3) in 2022, 2023 and 2050 are presented in Table 5. Developments in output and input prices can have dramatic impacts on output value, input expenditure and GVA and the choice of base year can be important in deriving percentage changes over time. For illustration, milk output value in 2023 was 30% lower than in 2022, reflecting a large reduction in international dairy commodity prices that occurred in 2023.

Under all scenarios modelled, milk output volumes increase relative to the current production level, with rates of growth in the volume of milk produced highest under S3 and lowest under S2. Under S1, over the period 2023-2050, milk output is projected to grow at an annualised rate of 1.15% per annum. Under S2 a slower rate of 0.9% per annum between 2023 and 2050 is projected. Under scenario S3, the higher agricultural activity scenario, milk production is projected to grow at 1.4% per annum between 2023 and 2050.

Under all scenarios modelled, the volume of beef output contracts relative to the 2022 level of production. The projected evolution of beef carcass output is driven both by developments in both the beef cow (suckler) and dairy cow breeding inventories. The projected growth in dairy cow numbers under each of the activity scenarios partially offsets the impact of the contraction in beef cow numbers that are projected. Under Scenario S1, beef output volume contracts at an annualised rate of -0.4% between 2023 and 2050. Under Scenario 2, beef production contracts at an annual rate of -1.1%. Under scenario S3, with faster growth in dairy cow numbers and slower rates of contraction in beef cow inventories, beef carcass output contracts by less than -0.5% per annum between 2023 and 2050.

The evolution of agriculture sectoral GVA (in nominal terms) over the period 2023 to 2050 is positive under all of the agricultural activity scenarios modelled. However, the projected rates of growth in GVA differ across the three agricultural activity scenarios modelled. Rates of growth in GVA are much lower under scenario S2 than under scenario S1, while in scenario S3 they are higher than under scenario S1.

The rate of inflation (personal consumption deflator) over the period 2023 to 2050 is projected to average 2% per annum (see Table 1). With the rate of price inflation exceeding the rate of growth in nominal GVA under scenario S1, in constant price terms, agricultural sectoral income is projected to contract. Under the low agricultural activity scenario S2, with growth in nominal GVA of less than 1% per annum, GVA in real terms is projected to contract significantly over the period to 2050. Under scenario S3, the higher agricultural activity scenario, the rate of growth in sectoral GVA is projected to marginally exceed the forecast rate of inflation over the period 2023-2050, and as a result real sectoral income is projected to grow.

Over the period to 2050, changes in the structure of agriculture (numbers of and size of farms) would be expected to occur both in response to the economics of agriculture but also broader (non-agricultural) economic developments. Structural change at the farm level would alter the relationship between projected sectoral level outcomes and farm level analogues. Exploring the consequence of such structural changes would require further research.

4 Emissions Mitigation Measure and Adoption Rate Methodology

In this section, the mitigation actions to deliver GHG mitigation in agriculture are described and the assumed level of adoption of the mitigation actions (based on two different levels of adoption) is explained.

4.1 Mitigation Measures and Adoption Rates

The set of mitigation measures analysed in Lanigan et al. (2023) were assessed for their potential to reduce agricultural GHG emissions over the period to 2050 in two different ways. The percentage reductions associated with enteric or manure methane mitigation measures were obtained from a literature survey of

Irish and UK research. Mitigation associated with such measures were then incorporated into a 'top-down' flow inventory approach based on the IPCC Good Practice Guidelines (IPCC 2019a). The analysis of mitigation used the same algorithms and emission factors as the Irish national GHG inventory (EPA 2024). The advantage of this approach is that the additive impacts of measures on national GHG emissions are assessed collectively. This also means that interactions between measures on GHG emissions could also be quantified in this type of MACC.

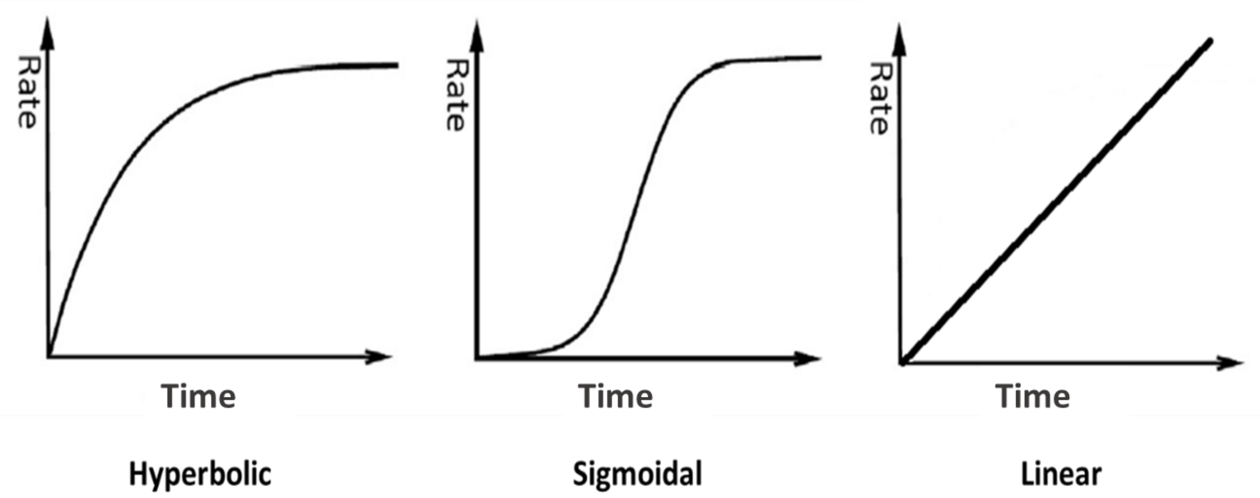
Emission sources attributed to 'agricultural emissions' primarily comprise of three gases. Methane (CH_4) is emitted during enteric fermentation and manure management. Nitrous oxide (N_2O) emissions arise from manure during both storage and subsequent land spreading onto soils, from excreted N during grazing, from the application of mineral fertilisers as well as indirect contributions from re-deposition of volatilised N and leached N. Agricultural carbon dioxide (CO_2) emissions arising from agriculture are relatively small and principally comprise of carbon dioxide emitted from lime and urea application to soils and from diesel consumption on farms.

Tier 2 national specific methodologies were used to generate a) methane from enteric fermentation and manure management as well as animal N excretion rates (EPA 2024, IPCC 2019a). Mineral fertiliser nitrous oxide emissions were generated using the national Tier 2 disaggregated emission factors (EF_1) (Harty et al. 2016, Roche et al. 2016). The pasture range and paddock (PRP) emissions were generated using a Tier 2 EF_3, disaggregated between urine N and dung N for bovines (Krol et al. 2016). All other nitrous oxide emission sources utilised Tier 1 default emission factors (IPCC 2019a). Carbon dioxide emissions from urea and lime were calculated based on the total amount of product applied, multiplied by the default IPCC carbon dioxide emission factor for lime and urea respectively, which assumed all C in both products are mineralised to carbon dioxide (IPCC 2019). Indirect nitrous oxide emissions arising from ammonia volatilisation and leached N were calculated using an N-flow sub model (Buckley at al. 2020). In this way, cross compliance with other environmental impacts, such as the National Emissions Ceilings (NEC) Directive and Nitrates Directive were taken into consideration.

MACC Measure Adoption Levels and Rate - Uncertainty & Sensitivity Analysis

- **Pathway 1 (P1) ambitious:** The first pathway has ambitious adoption rates similar to Pathway 2 in the 2023 Teagasc MACC (Lanigan et al. 2023), with measures aligning with those of the Food Vision Dairy and Food Vision Beef & Sheep Groups (Government of Ireland, 2022b, 2022c).
- **Pathway 2 (P2) very ambitious:** The second pathway assesses the impact of an even more ambitious set of adoption levels for the measures in the MACC. It extends the adoption rates in the 2023 MACC to the period to 2050. In many cases, the level of uptake assumed under P2, the very ambitious pathway, represents the maximum technically feasible adoption rate.
- **Variable rates of adoption:** Across the individual MACC measures, differential rates of uptake have also been included in order to reflect the differing levels of technology readiness of the individual measures. Well-established mitigation measures, such as fertiliser formulation, clover incorporation and lime application, have 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 the use of feed additives, a sigmoidal rate of uptake was assumed, i.e. where uptake was initially slow but then rapidly accelerates. Conversely, the uptake of Low Emission Slurry Spreading (LESS) has a front-loaded, convex curve-linear (hyperbolic) response fitted for the rate of uptake as all Nitrates derogation farmers have to apply slurry by LESS (Figure 7).

Figure 7: Diagrammatic representation of the three uptake rate response curves utilised in the Teagasc MACC analysis.



Source: Authors' own elaboration

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.). Table 6 below summarises our assumptions regarding uptake response rate by mitigation measure analysed with reference to assumptions made in the 2023 Teagasc MACC analysis (Lanigan et al. 2023).

Table 6: Uptake levels and response curve rate shape for individual Agricultural MACC measures.

	Uptake rate response curve	2018 situation	Pathway 2 2030 Uptake	2050 - Pathway 1	2050 - Pathway 2
Dairy EBI	**Linear**	**€190 per cow**	**€240 per cow**	**€360 per cow**	**€440 per cow**
Reduced Age of Finishing	Linear	25.2 months	3 months earlier with sexed semen	3 months earlier with 65% sexed semen	4 months earlier with 90% sexed semen
Feed Additives	Sigmoidal	0	**Efficacy:** 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). **Uptake:** Fed to 40% of spring calvers, 70% of autumn calvers, 45% of beef cattle.	**Efficacy:** 7% efficacy during grazing – fed to 60% of dairy cows **Housing:** Efficacy 15% (spring calvers) 25% (autumn calvers) 30% (beef cattle). **Uptake:** Fed to 50% of spring calvers, 70% of autumn calvers, 55% of beef cattle.	**Efficacy:** 7% efficacy during grazing up to 2028 – 20% post 2028 –10% efficacy in sheep **Housing:** Efficacy 15% (spring calvers) 25% (autumn calvers) 30% (beef cattle). 15% sheep **Uptake:** Fed to 60% of spring calvers, 90% of autumn calvers, 70% of beef cattle. 20% uptake in sheep
Diversification Impact on Livestock Numbers	Sigmoidal	0	137,963 LU reduction	240,027 LU reduction	366,286 LU reduction
Protected Urea + Nitrification Inhibitor	Linear	24% urea 3.5% CAN	85% CAN replaced with PU 100% Urea to PU	90% CAN replaced with PU 100% Urea to PU	100% CAN replaced with PU or PU+NI 100% Urea to PU

	Uptake rate response curve	2018 situation	Pathway 2 2030 Uptake	2050 - Pathway 1	2050 - Pathway 2
Compound fertilisers	Linear	20% of compounds are low nitrate	65% high NO_3 compounds replaced with low emission compounds	75% NO_3 compounds replaced with protected compounds	90% NO_3 compounds replaced with protected compounds
Liming	Linear	1.04M tonnes	Target held level from 2030	2.5 M tonnes by 2040	2.5 M tonnes by 2030
Clover & MSS	Linear	17 kha	757 kha	1.14 Mha	1.83 Mha
Acidification/ Amendments	Sigmoidal	0%	20% dairy/pigs 10% other	21% dairy/pigs 18% other	50% dairy/pigs 25% other
Slurry Aeration	Sigmoidal	0%	40% dairy/pigs 20% other	40% dairy/pigs 35% other	70% dairy/pigs 50% other
Phosphorus Impact on N_2O emissions	Linear		30% move to Index 3	25% move to Index 3	40% move to Index 3
Reduced Crude Protein	Linear	0% (current CP = 17%)	Both targets held level from 2030	2% CP reduction 40% Bovines, 3% reduction 40% Pigs	2% CP reduction 90% Bovines, 3% reduction 80% Pigs
Extended Grazing	Linear	227 days	Both targets held level from 2030	80 days extra grazing for 10% of bovine population	80 days extra grazing for 10% of bovine population

	Uptake rate response curve	2018 situation	Pathway 2 2030 Uptake	2050 - Pathway 1	2050 - Pathway 2
Low Emission Slurry Spreading	Hyperbolic	50%	80% uptake	100% uptake	100% uptake
Mineral Soil Drainage	Linear		Both targets held level from 2030	10% of poor-drained land	25% of poor-drained land
Digestate (biomethane)	Sigmoidal	2000 m^3	3,500,000 m^3 slurry	520,000 m^3 slurry (2030) 3,500,000 m^3 slurry by 2050	3,500,000 m^3 slurry (2030 to 2050)

Source: Authors' own elaboration

5 Projected Agriculture GHG emissions

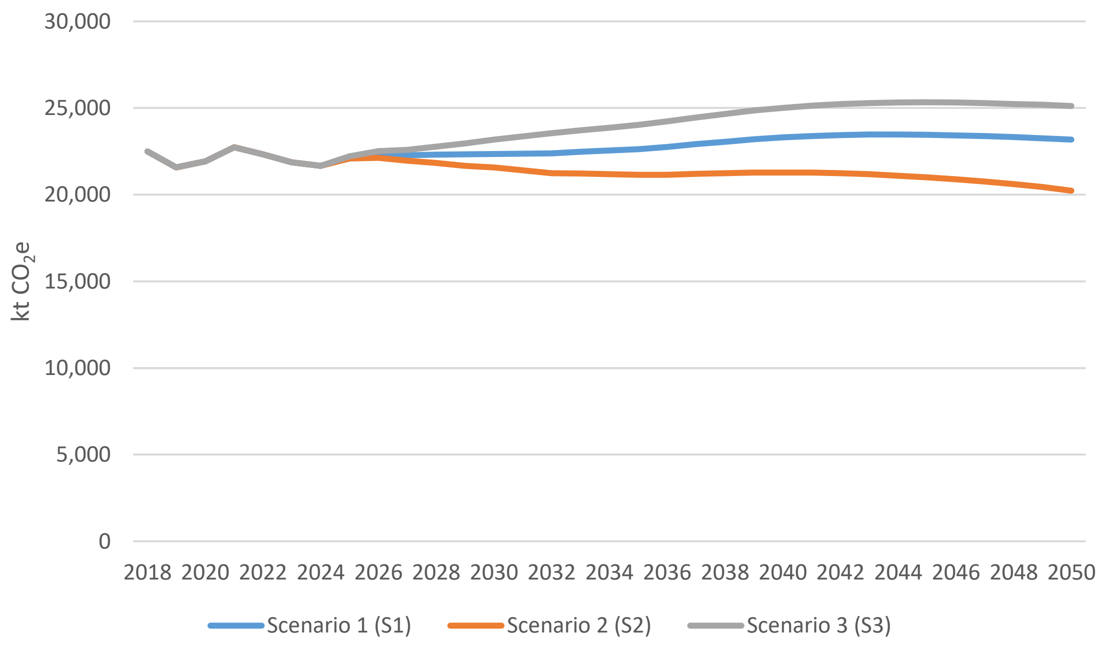
In this section, the mitigation that could be achieved in each of the three agricultural activity scenarios is quantified based on the two different adoption rates. As well as presenting the mitigation in carbon dioxide equivalents, the mitigation is also decomposed by individual GHG gas. The cost of the associated mitigation actions is also estimated. This then allows the presentation of the mitigation quantities and associated costs with the activity projected and mitigation pathway.

Our analysis focuses on comparing annual emissions over the period to 2050 with emissions in the base year (2018). Given the existence of a sectoral emissions ceiling for the agriculture sector for the period 2021-2030, projected cumulative emissions over this period are also presented relative to this ceiling. Cumulative emissions over subsequent budgeting periods, under each of the mitigation scenarios analysed, are also presented and compared with the allocated ceiling for carbon budget period 1 and period 2. These comparisons illustrate the degree to which projected cumulative emissions from the agriculture sector, under the alternative mitigation and agricultural activity scenarios, are associated with further reductions in GHG emissions and contributions to the national climate objective of climate neutrality by 2050.

5.1 Projected Emissions in the absence of Mitigation

In the absence of any GHG mitigation actions, agricultural GHG emissions in 2050, under S1, S2 and S3, are projected to be 23.2, 20.2 and 25.1 Mt CO_2e (equivalent to 23,171, 20,227 and 25,118 ktCO_2e). Under the base case scenario S1, the increased share of dairy cows in bovine breeding inventories and projected growth in milk yield per cow is reflected in growing GHG emissions despite overall stability in bovine animal inventories. Under the S2 (lower) and S3 (higher) agricultural activity scenarios, GHG emissions contract relative to 2018 base levels (S2) or under S3 grow more quickly than under S1.

Figure 8: Projected Agricultural GHG emissions under Scenario S1, S2 and S3 (BAU with no mitigation assumed).

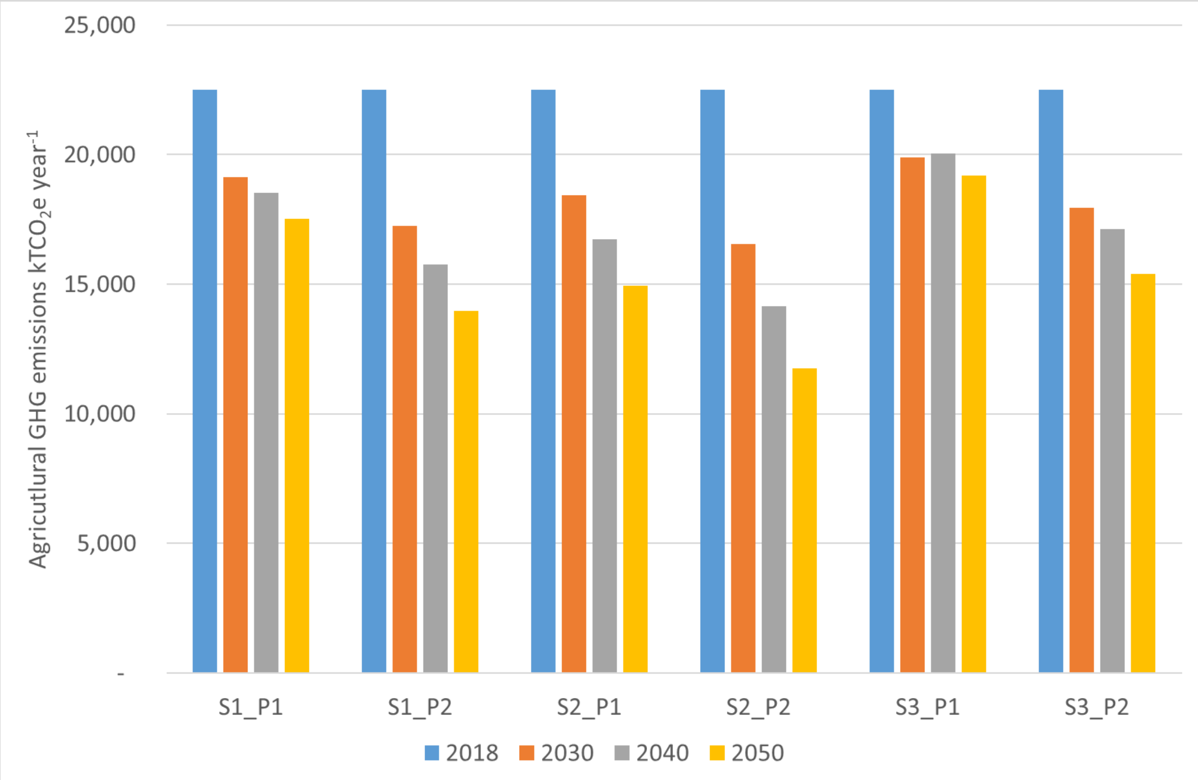


Source: Authors' own elaboration of EPA historical data and FAPRI-Ireland model 2024 projections

5.2 Projected Emissions under P1 and P2

The projected agricultural GHG emissions under each of the agricultural activity and mitigation scenarios are presented in summary for 2018, 2030, 2040 and 2050 (Figure 9).

Figure 9: Projected Agriculture GHG emissions (kTCO₂e) in 2018, 2030, 2040 and 2050 under the three agricultural activity scenarios (S1, S2 & S3) and two mitigation pathways (P1 ambitious & P2 very ambitious).



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

5.3 Projected agricultural emissions to 2030 under adoption pathways P1 and P2

Under all of the mitigation scenarios modelled, agricultural GHG emissions are projected to decline over the period to 2050. However, the magnitude of the projected decline in GHG emissions over the three decades 2021-2050 differ dramatically across the modelled scenarios and mitigation pathways.

Table 7: Projected Agriculture GHG Emissions (kt CO_2e year^{-1}) 2018, 2030, sectoral emissions ceiling and cumulative emissions 2021 to 2030.

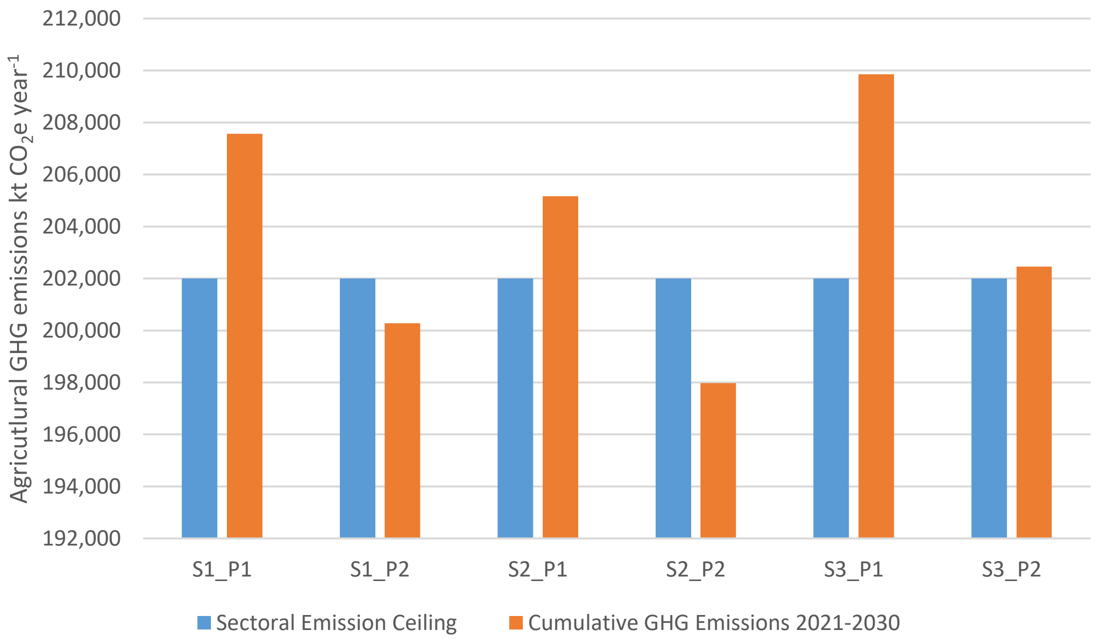
	Agriculture GHG 2018	Agriculture GHG 2030	Sectoral Emission Ceiling 2021-2030	Cumulative Emissions 2021-2030
S1_P1	22,502	19,140	202,000	207,564
S1_P2	22,502	17,233	202,000	200,282
S2_P1	22,502	18,418	202,000	205,168
S2_P2	22,502	16,560	202,000	197,973
S3_P1	22,502	19,904	202,000	209,856
S3_P2	22,502	17,950	202,000	202,454

Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

The projected agricultural activity levels under S1, S2 and S3 have been discussed above, as have different levels of ambition regarding changes in the technologies and farm management practices and activities under P1 and P2. Together the differing activity levels and adoption pathways are reflected in very different levels of projected GHG emissions produced by Irish agriculture in the period to 2050 (Figure 9). The largest reductions in GHG emissions relative to the base level in 2018 arise where the level of agricultural activity is stable or falling relative to the 2018 base level (S1 or S2) and/or where the rate at which mitigation measures are adopted is very ambitious (P2).

Ambitious levels of mitigation measure adoption under P1 are associated with reductions in emissions over time. However, the magnitude of the emissions reductions is insufficient to achieve the required 25% reduction in GHG by 2030 (Table 7) implicit in the sectoral emissions ceiling allocated to the agriculture sector by Government in 2022 (Government of Ireland, 2022a). Figure 10 illustrates the cumulative emissions of GHG over the first two Carbon Budget periods under the six agricultural GHG mitigation scenarios, together with the sectoral emissions ceiling allocated to agriculture. The results from the scenarios indicate that it is only when very ambitious adoption of GHG mitigation measures are assumed to occur (P2) that cumulative GHG emissions from agriculture remain within or close to within the allocated emissions ceiling for the 2021-2030 period. Where lower levels of ambition with respect to MACC measure adoption are assumed to prevail (as reflected in P1) cumulative agricultural GHG emissions are projected to exceed the allocated sectoral emissions ceilings (Table 7).

Figure 10: Cumulative Agricultural GHG emissions (kt CO_2e year^{-1}) and allocated sectoral ceilings 2021-2030 under the three agricultural activity scenarios (S1, S2 & S3) and two mitigation pathways (P1 ambitious & P2 very ambitious).

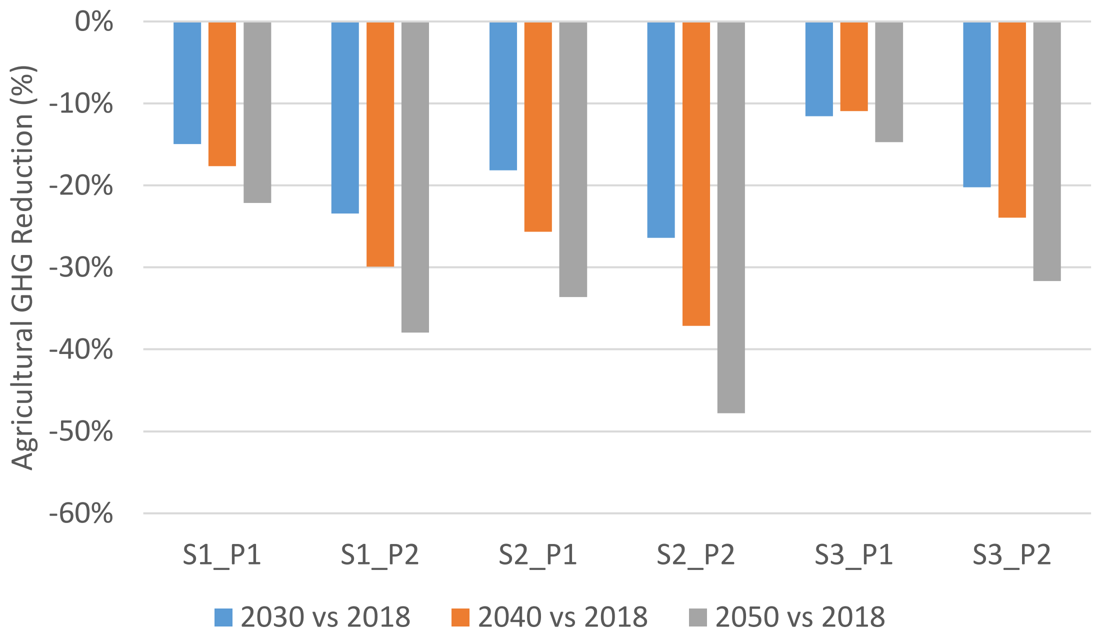


Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

5.4 Projected Agricultural Emissions to 2050 under pathway P1 and P2

The level of reduction in GHG emissions from agriculture projected to arise over the period to 2050 under each of the scenarios modelled reveals the continued importance of progress with respect to adoption of mitigation measures. Each of the six mitigation scenarios modelled is associated with reductions in GHG emissions relative to the 2018 base level (Figure 11). However, only those scenarios with very ambitious levels of adoption of mitigation actions are associated with emissions reductions that are significantly larger than those required to remain within the sectoral ceiling allocated to agriculture for the 2021-2030 period (Figure 10).

Figure 11: The percentage reductions in agricultural GHG emissions versus 2018 under the three agricultural activity scenarios (S1, S2 & S3) and two mitigation pathways (P1 ambitious & P2 very ambitious)



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

The S1 agricultural activity scenario and the ambitious P1 level of mitigation measure adoption emissions are projected to reduce by 22% in 2050 relative to 2018. Under the higher agricultural activity scenario (S3), the ambitious level of mitigation measure adoption (P1) is projected to lead to a 15% GHG emissions reduction by 2050 relative to 2018. To achieve reductions in emissions by 2050 that are greater than 25% (the 2030 reduction sectoral target) requires very ambitious levels of mitigation measure adoption (P2) over the period to 2050 or reductions in levels of agricultural activity (S2) that are associated with emissions of GHG and particularly those of methane. Only under Scenario 2, where there are dramatic reductions in the levels of bovine agricultural activity in Ireland over the period to 2050, is there a reduction in projected GHG emissions that significantly exceeds the 25% reduction required by 2030. Under S2, with dramatically lower levels of agricultural activity and the ambitious mitigation measure adoption pathway (P1), emissions in 2050 are projected to decline by 34% relative to 2018.

The scenario analysis indicates that agriculture GHG emissions can be expected to decline significantly where a very ambitious levels of mitigation measure adoption is combined with a reduction in activity levels, contributing to the national climate policy objective of achieving a competitive, low-carbon, climate-resilient and environmentally sustainable economy by 2050.

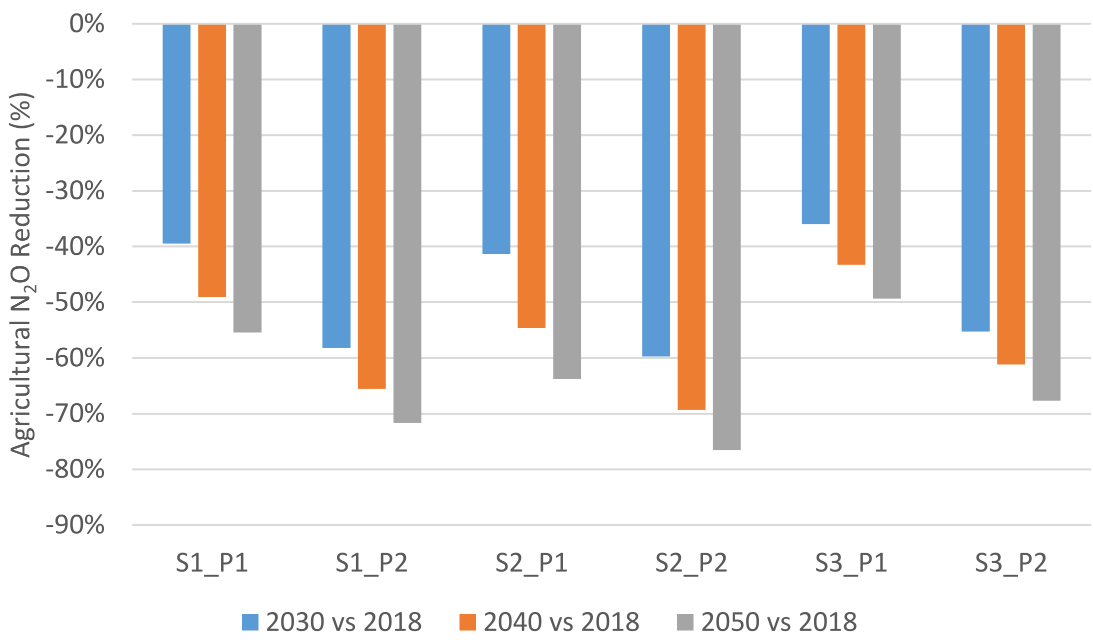
Under Scenario 1, with very ambitious levels of mitigation measure adoption (P2), it is possible for agriculture GHG emissions to be reduced by 38% by 2050 as compared with 2018. Under the lower agricultural activity level scenario (S2), with a very ambitious level of GHG mitigation measure adoption (P2), agricultural GHG emissions were projected to reduce by 48% in 2050 relative to 2018. The Agriculture GHG emission in 2018 and projected 2050 emissions under S1, S2 and S3 for the BAU, P1 and P2 are summarised in Table 9. The associated cumulative agricultural GHG emissions for the individual six carbon Budget Periods 2021-2050 are also presented in Table 9.

5.5 Projected agriculture GHG reduction by individual gas

The very significant reductions in GHG emissions that are possible with very ambitious levels of mitigation measure are driven by the assumed greater uptake of methane mitigation measures under P2. In 2018 emissions of methane by the agricultural sector accounted for 73% of agricultural emissions, nitrous oxide accounted for 25% of agriculture GHG emissions, with emissions of carbon dioxide accounting for the remaining 2% of total agricultural emissions (Figure 12). To achieve reductions that go significantly further than the 2030 25% reduction target requires significant further reductions in methane emissions over the period to 2050.

In all of the mitigation scenarios, modelled emissions of nitrous oxide decline dramatically. By 2050, emissions of nitrous oxide are projected to have declined between 49% and 77%. Many of the nitrous oxide mitigation measures are very well understood and have a high level of technological readiness. With an ambitious (P1) level of mitigation measure adoption, nitrous oxide emissions decline by 55% (S1) and 64% (S2) in 2050 relative to 2018. Under the very ambitious (P2) levels of mitigation measure adoption (P2) the projected nitrous oxide emissions decline by 72% (S1) and 77% (S2) in 2050 relative to 2018. Even under the higher agricultural activity scenario S3, the reductions in nitrous oxide under both P1 and P2 are very large, ranging 49% (P1) to 68% (P2) in 2050 relative to 2018.

Figure 12: Change in Agricultural N_2O emissions versus 2018 under the three agricultural activity scenarios (S1, S2 & S3) and two mitigation pathways (P1 ambitious & P2 very ambitious).

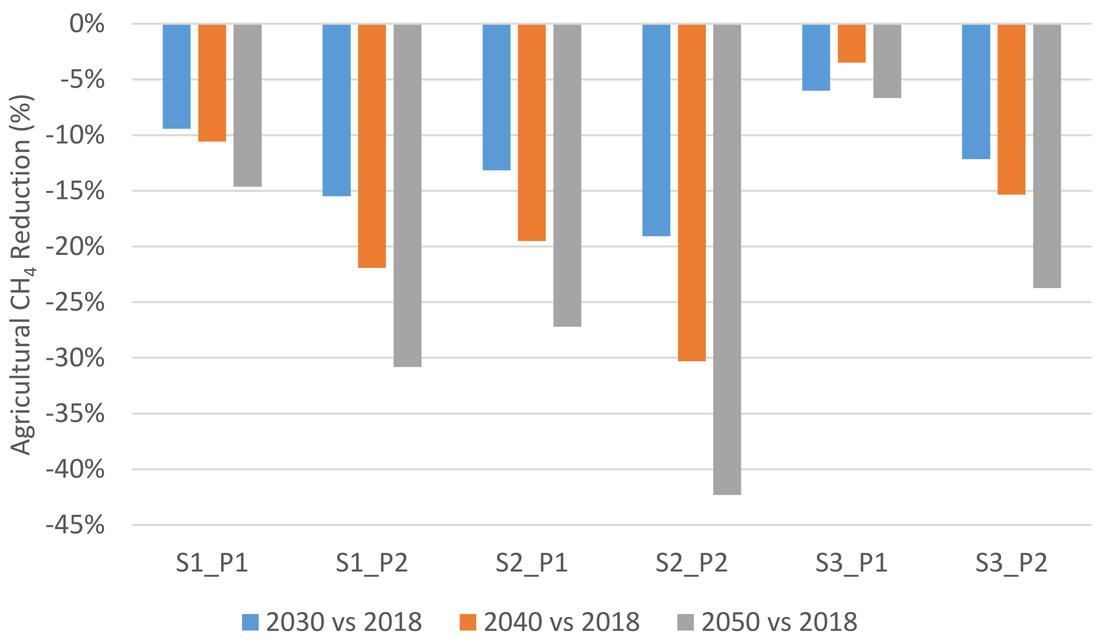


Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

The projected reductions in methane emissions differ dramatically between mitigation measure adoption pathways P1 and P2 and are considerably lower than the projected reduction in nitrous oxide emissions. This reflects the technical difficulty of mitigating methane emissions, which in turn is reflected in the assumed rate of methane measure mitigation uptake and the efficacy of methane mitigation measures when compared to measures that are focused on mitigating emissions of nitrous oxide.

Under all of the mitigation scenarios, emissions of methane are projected to decline as illustrated in Figure 13. The projected decline is greatest under those mitigation scenarios with very ambitious rates of mitigation measure adoption (P2) and where the numbers of cattle are either stable (S1) or declining over the projection period. Under S1, and the very ambitious mitigation measure adoption pathway (P2), methane emissions are projected to decline by 31% in 2050 compared to 2018. This level is in excess of the commitment to reduce fossil and non-fossil methane emissions by 30% by 2030 set out in the Global Methane Pledge (European Commission and United States of America, 2021) and is within the 24% to 47% reduction in global biogenic methane emissions by 2050 (UNFCCC, 2018). Under the lower agricultural activity projection (S2) and the very ambitious mitigation measure adoption pathway (P2), emissions of methane by Irish agriculture are projected to decline by 42% in 2050 compared to 2018.

Figure 13: Change in Agricultural CH_4 emissions by mitigation scenario modelled versus 2018 under the three agricultural activity scenarios (S1, S2 & S3) and two mitigation pathways (P1 ambitious & P2 very ambitious).



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

The mitigation of GHG emissions by gas differs greatly, reflecting the differing levels of technological readiness of nitrous oxide and methane mitigations measures and the relative efficacy of these measures (Table 8). Measures that mitigate emissions of nitrous oxide are expected to be more rapidly taken up by farmers and more efficacious than measures which mitigate emissions of enteric methane. Methane emission mitigation measures either have a slow rate of deployment – such as animal breeding measures like EBI, which has a biological constraint, or are at a technological readiness level that will mean that their adoption will likely occur in later carbon budgeting periods.

Table 8: Change in Agriculture GHG emissions by Gas 2050 vs 2018.

	Change in N_2O	Change in CH_4	Change in CO_2	Change in CO_2e
	% Δ 2050 vs 2018			
S1_P1	-55%	-15%	89%	-22%
S1_P2	-72%	-31%	90%	-38%
S2_P1	-64%	-27%	80%	-34%
S2_P2	-77%	-42%	78%	-48%
S3_P1	-49%	-7%	94%	-15%
S3_P2	-68%	-24%	95%	-32%

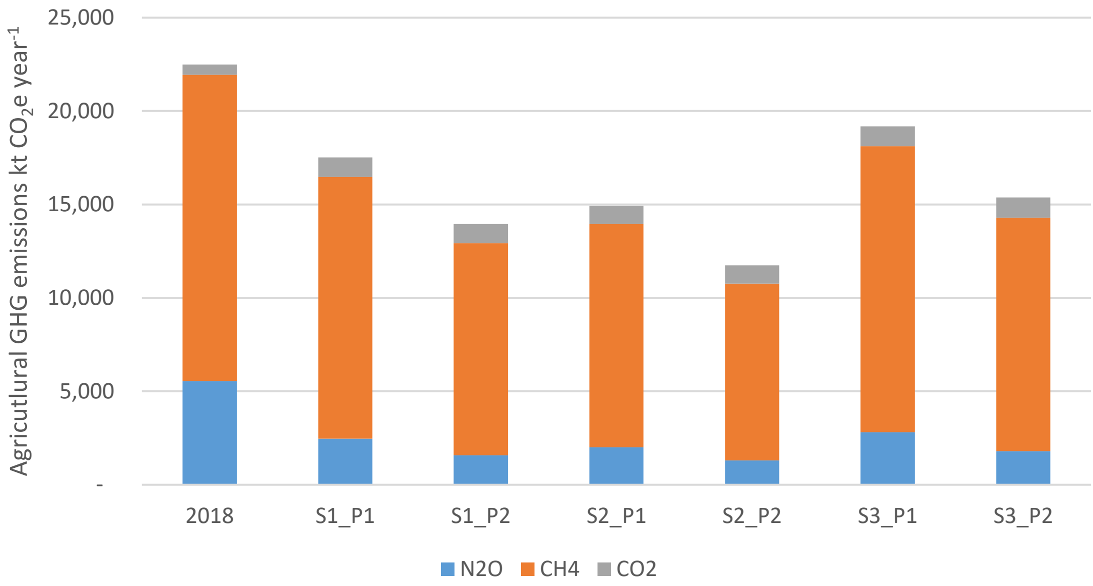
Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

The mitigation adoption rates for reducing nitrous oxide emissions are front-loaded into the first two carbon budgeting periods, as they are commercially available to farmers now. This adoption will still need considerable effort by policy makers and industry to achieve the very high adoption rates required. In contrast, the projected reductions in methane emissions are more evenly spread across the six carbon budget periods. Nitrous oxide measures are ready to be deployed and the majority of these measures have linear or front-loaded (hyperbolic) uptake paths. 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/new industries or demonstration/advisory investment (e.g. manure additives, diversification, lipids, digestate) to support uptake.

While emissions of both nitrous oxide and methane are projected to decline under all mitigation scenarios modelled, emissions of carbon dioxide are projected to increase strongly due to the projected uptake of the liming and the fertiliser formulation measures (Table 8). Both of which are associated with increased emissions of carbon dioxide that partially offset the reduced emissions of nitrous oxide that they support. By 2050, under Scenario 1, with the very ambitious pathway for mitigation measure adoption, emissions of carbon dioxide are projected to increase to 1,042 kt CO_2e in 2050 or by close to 90% relative to their 2018 level.

In 2018, the share of methane, nitrous oxide and carbon dioxide in total agricultural emissions were respectively 73%, 25% and 2%. Under all of the GHG mitigating scenarios analysed, the relative share of nitrous oxide, methane and carbon dioxide change dramatically (Figure 14). By 2050 under S1, where farmers follow the very ambitious (P2) pathway of mitigation measure adoption, the share of nitrous oxide in total agricultural greenhouse gas emissions declines dramatically, while the share of methane and carbon dioxide increase. This pattern is repeated across all of the scenarios modelled and reflects the degree to which a very large share of nitrous oxide emissions are mitigated in all scenarios analysed. The greater difficulty of mitigating methane emissions in agriculture is reflected in the increasing share of Irish agriculture emissions that are projected to be accounted for by methane. This is despite the large reductions in methane emissions that are achieved, particularly in those scenarios where MACC measure uptake is very ambitious (P2), with the share of GHG emissions made up of methane increases from 73% in 2018 to 81% in 2050. The annual disaggregated CH_4, N_2O and CO_2 emissions for Scenario 1 under BAU, Adoption Pathway 1 and Pathway 2 are presented in Figure 15.

Figure 14: Agriculture GHG Emissions (kt CO_2e year^{-1}) in 2018 and 2050 by Gas and Mitigation Scenario



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

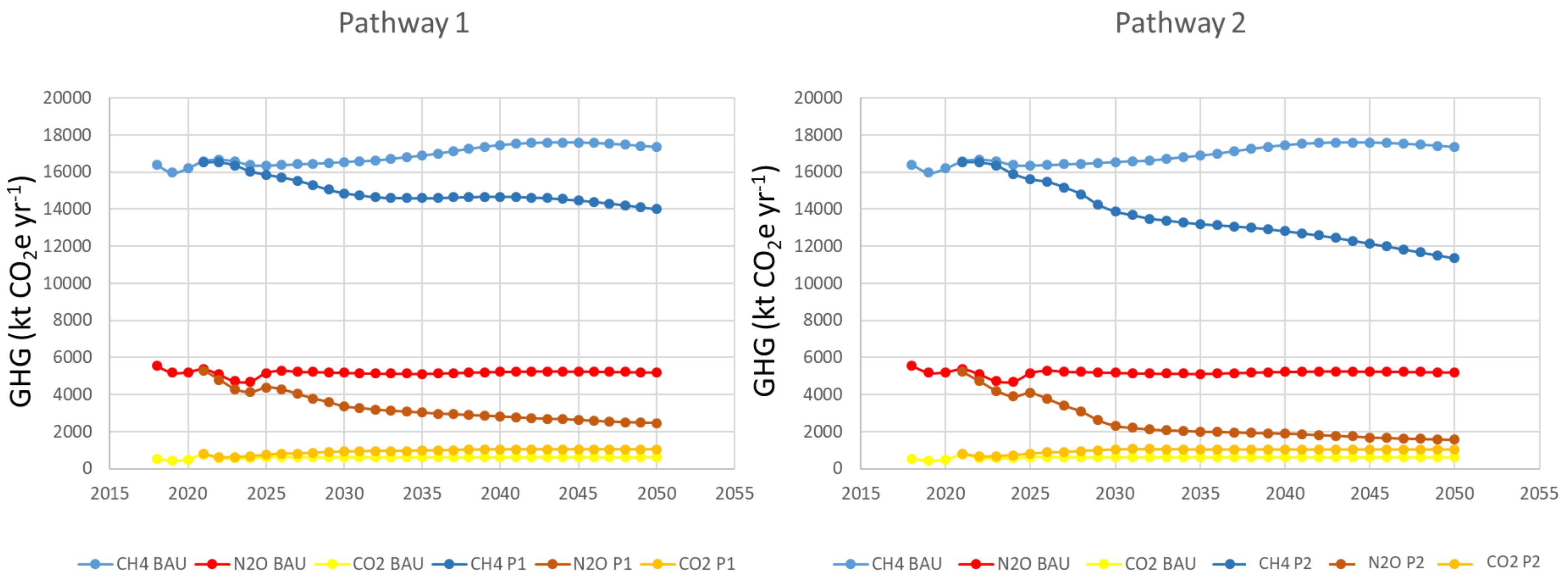
Table 9: Agriculture GHG emission in 2018 and projected 2050 emissions under S1, S2 and S3 with Carbon Budget Periods 2021-2050

Scenario	Pathway	2018 GHG emissions*	Emissions in 2050	CB1 Cumulative emissions	CB2 Cumulative emissions	CB 3 Cumulative emissions	CB 4 Cumulative emissions	CB 5 Cumulative emissions	CB 6 Cumulative emissions
		$ktCO_2e\ yr^{-1}$	$ktCO_2e\ yr^{-1}$	$ktCO_2e$	$ktCO_2e$	$ktCO_2e$	$ktCO_2e$	$ktCO_2e$	$ktCO_2e$
S1	BAU	22,502	23,171	110,764	111,567	112,405	115,231	117,227	116,544
S2	BAU	22,502	20,227	110,698	109,143	106,180	106,130	105,785	102,927
S3	BAU	22,502	25,118	110,829	113,999	118,498	123,197	126,304	126,144
S1	P1	22,502	17,517	107,717	99,847	93,694	92,836	91,615	88,854
S2	P1	22,502	14,937	107,624	97,544	88,013	84,667	81,499	76,914
S3	P1	22,502	19,186	107,751	102,105	99,179	99,896	99,553	97,161
S1	P2	22,502	13,962	106,720	93,563	82,775	79,908	76,321	71,635
S2	P2	22,502	11,748	106,613	91,360	77,556	72,524	67,371	61,297
S3	P2	22,502	15,379	106,739	95,716	87,828	86,274	83,317	78,766

Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

*** Excludes fossil fuel emissions**

Figure 15: Disaggregated CH_4, N_2O and CO_2 emissions for Scenario 1 under BAU, Adoption Pathway 1 and Pathway 2



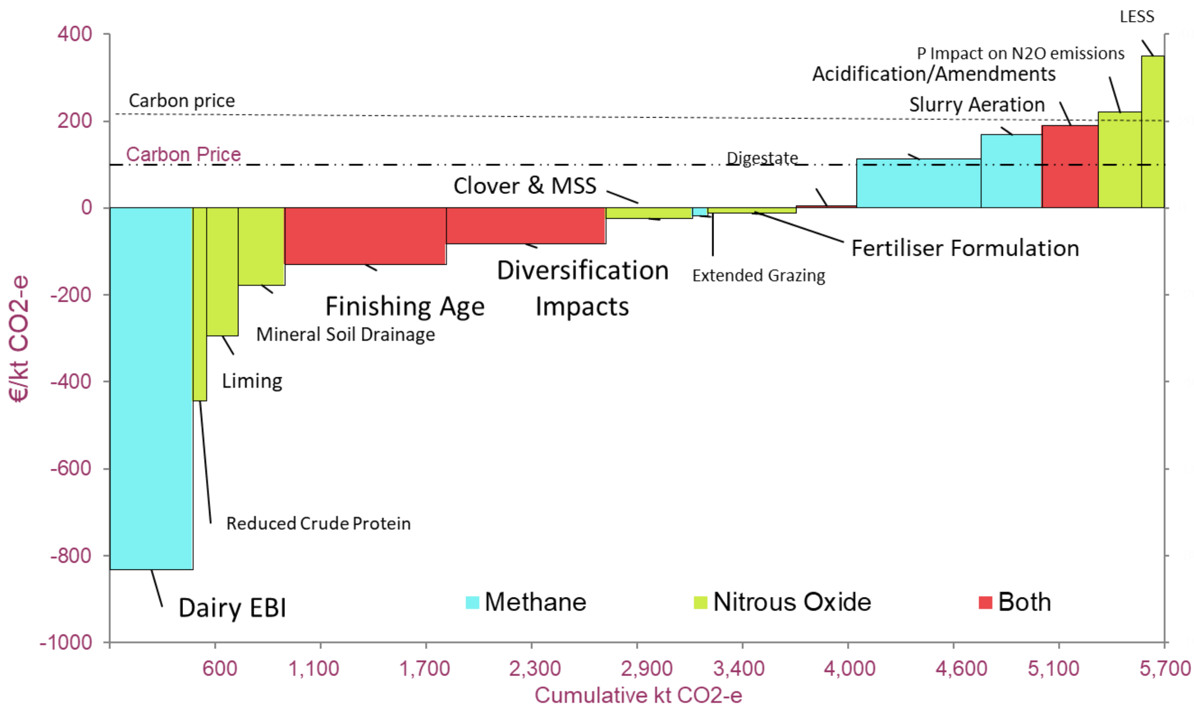
Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

5.6 Contribution of Individual Measures and Costs of Mitigation under S1

There is no single silver bullet measure, which can be relied upon to deliver a large share of the mitigation over the period 2021-2050. Across the mitigation scenarios modelled, a number of individual measures accounted for a large share of the mitigation potential. In scenario 1 pathway 1, 70% of the mitigation is achieved by: Reduced Age of Finishing (18%), Feed Additives and Supplements (12%), Fertiliser Formulation (12%), Diversification Impacts (11%), Dairy EBI (9%) and Clover/Multi-species swards (8%). The same group of measures accounted for 68% of the total mitigation potential under scenario 1 pathway 2. The marginally reduced share of cumulative abatement associated with the same six measures was due to the higher ambition under P2 in terms of reducing manure management emissions (slurry aeration and acidification).

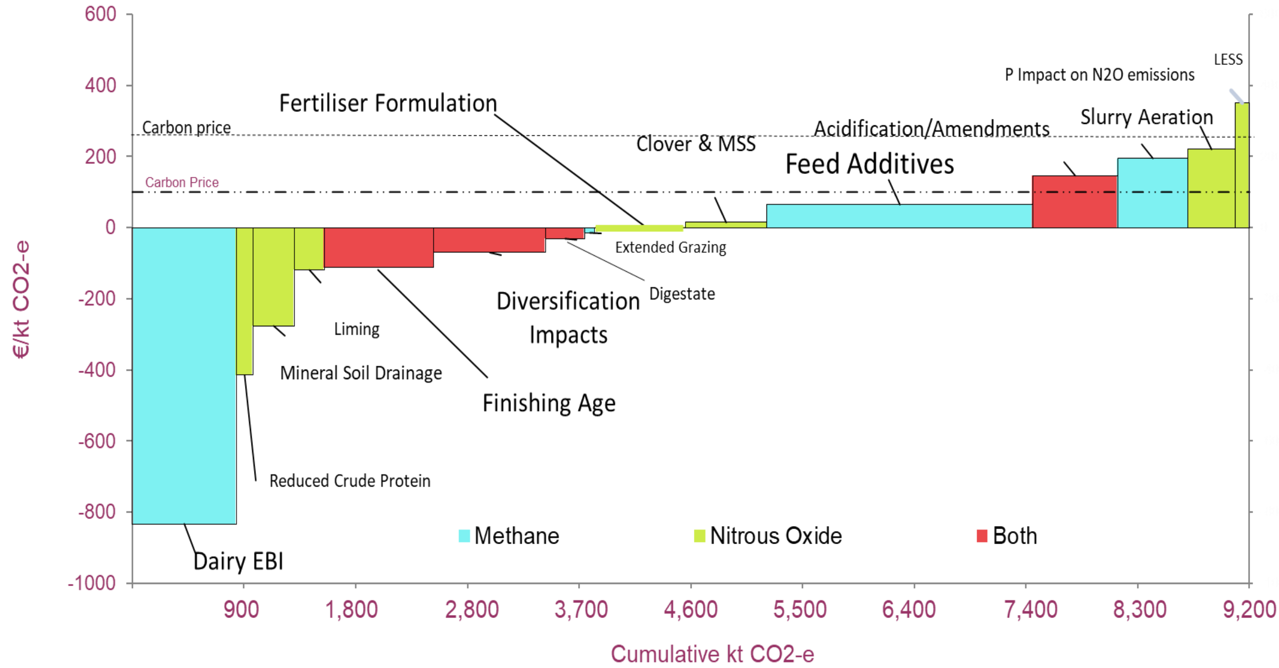
The ranking of mitigation measures in terms of their cost-benefit is shown for scenario 1 pathway 1 (Figure 16) and scenario 1 pathway 2 (Figure 17). These are the abatement potentials and their associated cost/kt CO_2e in the year 2050.

Figure 16: Marginal Abatement Cost Curve for agriculture measures under Scenario 1 with Pathway 1 Adoption Rates. Values represent the maximum yearly abatement in 2050. Dashed line indicates Carbon cost of €100 and €250 t^{-1} CO_2.



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

Figure 17: Marginal Abatement Cost Curve for agriculture measures under Scenario 1 with Pathway 2 Adoption Rates. Values represent the maximum yearly abatement in 2050. Dashed line indicates Carbon cost of €100 and €250 t^{-1} CO_2



Source: Authors' own elaboration based on EPA National Inventory Report 2024, FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

5.6.1 Cost-Negative Measures

For Pathway 1 uptake, the most cost-beneficial (i.e. negative costs) measures were reducing the age of bovine finishing and dairy EBI. Both of these measures primarily tackle methane emissions.

Reduced age of bovine finishing

By 2050, reducing the age of finishing beef cattle is projected to reduce emissions by 867 kt CO_2e yr^{-1} and 904 kt CO_2e yr^{-1} at a cost saving of circa -€163 t^{-1} CO_2e by 2050 for Pathway 1 and 2 respectively (Figures 16 and 17). This equates to almost 18% and 10% of total mitigation in the year 2050 under Pathways 1 and 2, respectively. This measure is co-dependent on improving beef cattle breeding traits, such as maternal traits (fertility, calving performance) as well as on improving terminal traits, such as increasing cattle live weight gain. In addition, this measure is predicated on the wider use of sexed semen within the dairy herd (65% in order to confer 'beef traits' into non-dairy replacements). Over the period 2010 to 2023, there has been substantial progress made in reducing the age at which bovine animals are finished in Ireland. It was projected that a mean 60 day (Pathway 1) to 90 day reduction (Pathway 2) in finishing age could be achieved over the remainder of this decade, with a further 30 day reduction spread over the following two decades 2030 to 2050.

Dairy EBI

Dairy EBI delivered 449 kt CO_2e yr^{-1} (Pathway 1) and 859 kt CO_2e (Pathway 2) by 2050 under S1 and was the most cost-negative measure, with cost savings ranging from -€690 t^{-1} CO_2e to -€996 t^{-1} CO_2e. Methane savings were made, because methane yields (Y_m) of high EBI cows have been found to be lower than those of lower EBI cows (Lahart et al. 2021). The magnitude of cost savings reflected the fact that increasing fertility rates, calving performance, milk production per head and reducing the need for replacements was highly successful at both improving farm profitability within the dairy sector and lowering the methane yield of cows.

Other Cost Negative Measures

The other principal cost-negative measures for Pathway 1, in terms of delivering cumulative reductions across the entire period, were use of **altered fertiliser formulation** and the use of **clover and multi-species swards**, which together reduce nitrous oxide emissions by 20% by 2050. In order for clover establishment to be successful, soil pH and nutrient status must be optimal, so this measure is co-dependent on **'Liming'** and '**P impact on nitrous oxide'** measures. It should also be noted that the fertiliser formulation measure comprises three sub-measures:

1. The substitution of Calcium Ammonium Nitrate (CAN) and straight urea with Urea with urease inhibitors, NBPT, NPPT or 2NPT (Harty et al. 2016, Roche et al. 2016)
2. The replacement of high nitrate compounds (e.g. 27-2.5-5) with ammonium-based compounds (Rahman & Forrestal 2021, Gebremichael et al. 2021)
3. The substitution of CAN with Urea with urease inhibitors and a nitrification Inhibitor incorporated into the granule under Pathway 2 only (Harty et al. 2016).

The utilisation of all N saving measures, such as use of clover, liming and P nutrient status and wider use of LESS means that less mineral N would be required in order to maintain the same level of agricultural production with **reduced chemical N Fertiliser use**. Since 2021, fertiliser use has decreased by 32% from 399,164 tN yr^{-1} to 280,569 tN yr^{-1}, but this reduction in use has been driven mainly by dramatically increased fertiliser prices. The projected level of fertiliser use in 2050 under both pathways for all three Scenarios are shown in Table 10. The lowest levels of projected fertiliser use are associated with very ambitious mitigation measure adoption pathways (P2) and/or lower levels of agricultural activity (S2).

Table 10: Projected 2050 fertiliser use (tN yr^{-1}) for all Mitigation Scenarios.

Scenario		S1_P1	S1_P2	S2_P1	S2_P2	S3_P1	S3_P2
Fertiliser N-use	*tN yr^{-1}*	217,182	177,544	144,266	104,628	265,985	217,348

Source: Authors' own elaboration based on FAPRI-Ireland model 2024 and Teagasc MACC (Lanigan et al., 2023)

5.6.2 Cost-positive measures - Additives

Most cost-positive measures were those associated with methane abatement.

Feed Additives

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 2050, under Pathway 1, the use of feed additives to reduce methanogenesis was primarily considered to occur during the housing period, or during milking while cows are grazing. Efficacy of the additives during housing was assumed to be between 15%-25% dependent on animal type and 7% during grazing. This difference in efficiency was due to the fact that during grazing animals could only be dosed twice daily (during milking). Uptake was assumed to be sigmoidal in nature (i.e. slow to begin with, but accelerating in response to policy) and was projected to deliver 672 ktCO_2e yr^{-1} or 12% of annual mitigation at a cost of between €114 - €199 $t^{-1}CO_2e$ (Figure 4).

Pathway 2 adoption assumed a) much wider adoption of feed additives with 90% of dairy cows dosed with a feed additive during grazing and the majority (>70%) of bovines fed additives during the housing period. The grazing efficacy of additives was increased to 20% as additives other than 3-NOP were assumed to start entering the market under this adoption pathway. Sheep were assumed to receive feed additives in this pathway, a mitigation action that had not previously been included. This resulted in a larger abatement of 2,195 ktCO_2e yr^{-1} or 16% of annual mitigation at a cost of €66 $t^{-1}CO_2e$ to €158 $t^{-1}CO_2e$ (Figure 5) by 2050.

Manure management

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 land spreading and reduce methane and ammonia during storage by 70%-90% (Brennan et al. 2011, 2015, Kavanagh et al. 2021). Slurry aeration also reduces methane by introducing oxygen into slurry, which reduces the amount of methanogenesis (which is an anaerobic process). 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, Mostafa et al. 2019, Ambrose et al. 2023). However, slurry aeration may 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). Under Pathway 1, both of these measures combined were estimated to reduce emissions by 634 kt CO_2e yr^{-1}, with Pathway 2 adoption delivering 1,281 kt CO_2e yr^{-1}, due to the increase in the uptake of this measure on dairy and pig farms.

Diversification

The national policy position regarding an expansion of both organic farming and forestry is to increase the area under organic farming to 7.5% of utilisable agricultural area by 2027 and to achieve an 8,000 annual forestry planting rate by 2030. Similarly, between 130,000 and 156,000 ha of grassland may be required to provide feedstocks for a biomethane industry capable of delivery the targets set out in the recently published National Biomethane Strategy (Government of Ireland, 2024).

The implications for agricultural GHG emissions of an increase in land area in organic farming will largely be mediated through: reduced use of inorganic fertilisers, 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. Many of these effects have been considered in other individual measures included in the MACC (e.g. reduced N due to an increase in organic farming is incorporated in the assumed reduction in inorganic N fertiliser derived from the 'Liming' and 'Clover & MSS' measures). In this analysis, it was assumed that there was a small reduction in stocking rates (12.5% per ha) in response to conversion to organic farming. This modest reduction is principally because the majority of farms opting to change to organic production already had low stocking rates (circa. 1 LU ha^{-1}). Therefore, the overall impact of a transition to organic production on the national cattle population was expected to be relatively modest.

In terms of the other diversification measures (forestry, the increased proportion of tillage and the use of land to produce biomethane feedstocks or for solar PV), it was assumed that half of the stocking rate per hectare (mean stocking rate = 1.2 ±0.15 LU ha^{-1} depending on activity scenario used) was displaced with an increased stocking rate for the remainder of the farm.

Under Scenario 1 livestock displacement is projected by 2050 to have reduced animal number by 240,000 Livestock Units (P1) and 366,000 Livestock Units (P2), resulting in emissions reduction from 854 ktCO2e (P1) and 918 (P2) ktCO_2e $year^{-1}$.

6 Conclusions/Summary

- **Scenario S1 (Base Case):** In this scenario, by 2050 dairy cow numbers rise by 14%, increasing total milk production by 38% due to higher milk yields. Total cattle inventories decrease by 7%, while beef production declines by 11%. Fertiliser use is projected to rise by 10%, and cropland area shrinks by 16% as grassland farming, especially dairying, becomes more profitable. Sheep numbers drop by 25%, while pig and poultry production grows by 25% and 30%, respectively.
- **Scenario S2 (Lower Agricultural Activity):** With reduced economic incentives for dairy and beef in this scenario, by 2050 total cattle inventories drop by 22%, driven by an 84% decline in beef cow numbers. Dairy cow numbers still rise by 7%, and with higher milk yields, milk production increases by 28%, but beef production falls 26% by 2050. Fertiliser use decreases by 12%, cropland contracts by 14%, and sheep numbers drop by 25%. Pig and poultry production grows by 25% and 35%.
- **Scenario S3 (Higher Agricultural Activity):** Higher milk prices and support for beef farmers lead to a 22% increase in dairy cow numbers by 2050 and a slower decline in beef cow numbers than in the other two scenarios. Total cattle inventories grow by 1%, milk production rises by 47% and beef production drops by less than 5%, a smaller decrease compared to S1 and S2. Fertiliser use rises by 22%, cropland area contracts by 24%, and sheep numbers decline by 25%. Pig and poultry production grow by 24% and 34%.
- **Projected Greenhouse Gas Emissions in 2050**
  - **No mitigation (BAU)**: The projected emissions in 2050 for S1, S2 and S3 without any emissions mitigation in 2050 were 23,171, 20,227, and 25,118 ktCO_2e, respectively. Emissions without any mitigation are projected to decrease by 0.7% under S1 and 4.2% under S2. Emissions from agriculture without any mitigation are projected to decrease by 3.0% under scenario S3.
  - **Ambitious adoption rates (Pathway 1):** The projected emissions in 2050 for S1, S2 and S3 were 17,517, 14,937 and 19,186 ktCO_2e, respectively. These imply emission reductions of 22% (S1), 34% (S2) and 15% (S3) in 2050 compared to 2018.
  - **Very ambitious adoption rates (Pathway 2)**: The projected emissions in 2050 for S1, S2 and S3 were 13,962, 11,748 and 15,379 ktCO_2e, respectively. These imply emission reductions of 38% (S1), 48% (S2) and 32% (S3).

Mitigation Results in Carbon Dioxide Equivalents by 2050:

- Scenario 1: emissions decrease by 22% (P1) and 38% (P2).
- Scenario 2: emissions decrease by 34% (P1) and 48% (P2).
- Scenario 3: emissions decrease by 15% (P1) and 32% (P2).

Mitigation Results by Individual Gases by 2050:

- **Scenario 1:** Methane emissions fall 15%-31% and nitrous oxide emissions drop by 55%-72%.
- **Scenario 2:** Methane emissions fall 27%-42%, while nitrous oxide emissions fall by 64%-77%.
- **Scenario 3:** Methane emissions fall 7%-24%, while nitrous oxide emissions fall by 49%-68%.
- Across all scenarios, nitrous oxide reductions are projected to occur primarily by 2030, while methane reductions are achieved more gradually over the period to 2050.

Key Takeaways for Policymakers

- **Significant Emission Reductions Require Ambitious Mitigation Efforts:** Achieving substantial reductions in agricultural GHG emissions by 2050 necessitates a very ambitious adoption of technical mitigation measures (P2). These high levels of uptake would allow the agriculture sector to contribute significantly to Ireland's national climate goals, including achieving the 25% reduction target for agriculture by 2030 and delivering further reductions in GHG emissions by 2050. The potential reductions in agricultural emissions has been calculated at between 38% (S1) and 48% (S2) by 2050 relative to 2018.

- **Agricultural Activity Levels Affect GHG Mitigation Potential:** Scenarios where agricultural activity is stable (S1) or reduced (S2) yield the largest GHG reductions relative to the 2018 level, particularly when coupled with very ambitious mitigation measures. Scenario S3, which involves higher agricultural activity, achieves lower reductions in GHG emissions, highlighting the challenge of achieving emissions reductions from the agriculture sector when aggregate agricultural activity levels are increasing.

- **Reducing Methane Emissions is Technologically Challenging:** While significant reductions in nitrous oxide emissions are feasible due to well-developed mitigation measures, reducing enteric and manure methane emissions poses greater technological challenges. Methane mitigation technologies, like feed additives and manure management, are more costly and slower to deploy and at a generally lower level of technological readiness.

- **Cumulative GHG Emissions Exceed Sectoral Ceilings without Very Ambitious Mitigation Measure adoption:** Without very ambitious mitigation efforts (P2), agricultural emissions will likely exceed the sectoral emissions ceilings allocated for 2021–2030. This highlights the need for rapid and extensive implementation of mitigation technologies.

- **No Single Mitigation Measure Delivers a Substantial Share of GHG Emissions Reductions:** A wide range of mitigation measures contribute to reducing emissions, with no single measure providing a dominant share of the mitigation potential. Key contributors include reducing the age of cattle finishing, use of feed additives, fertiliser reformulation, and improved breeding practices like Dairy EBI.

- **Methane Reductions are Associated with Higher Costs:** Methane mitigation measures, particularly feed additives and manure management options, are among the most costly, while some reduction measures, such as reducing the age of cattle finishing and Dairy EBI, result in cost savings. It can be expected that economic considerations will play a significant role in determining the feasibility of widespread methane mitigation and Government and industry support to farmers will be required to achiever very ambitious rates of measure adoption.

- **Increased Carbon Dioxide Emissions Result from Certain GHG Mitigation Measures:** Some mitigation strategies, such as liming and fertiliser reformulation, result in increased carbon dioxide emissions, partially offsetting reductions in other gases. This indicates the need for holistic consideration of trade-offs between different GHG gases.

- **Achievement of Long-Term Agricultural GHG Reduction targets will Require Consistent and Very Ambitious Mitigation Efforts:** If ambitious mitigation measures are continuously adopted, agricultural emissions could decrease by between 15% and 48% by 2050. The variation in mitigation depends on the activity scenario used and the abatement adoption pathway. Achieving such reductions would be a significant step towards the 2050 goal of climate neutrality.

- **Policy and Incentives are Key to Achieving Emissions Reductions**: There is a need to rapidly adopt the mitigation measures highlighted in the analysis. The very high rates of adoption for many measures, which exceed 70%, could only be achieved through targeted policies and incentives. Advisory and extension services will guide farmers and land-owners on the path to reduced GHG emissions by 2030 and to achieving further reductions in GHG emissions over the period to 2050.
- **Importance of Viable and acceptable Farm Diversification Options:** In all of the mitigation scenarios modelled the diversification measures were important contributors to reducing GHG emissions. Government and industry support for such alternative land uses will be critical in achieving the projected impact of these measures on agriculture sector GHG emissions.
- **Need for Continuing Research and Innovation**: There is a need for continuing research and development of emission mitigation technologies to identify new practices to reduce agricultural and land-use emissions. Research is also needed to further refine that agricultural and land-use inventories to reduce uncertainty and provide inventory ready mitigation measures available for adoption by farmers.

Appendix 1

Mitigation Costs

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 incomes associated with the changes in farming activities and outputs. The costs and benefits were evaluated at two different cost levels: one (low-cost) based on 2020 prices (prior to Russia's illegal invasion of Ukraine) and the second based on 2022 prices.

The costs are the marginal costs per annum for the quantity of CO_2-e abated. 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 would incur as a result of adoption of an abatement measure. This includes the annualised cost of additional capital, repairs, fuel and labour costs as well as any negative costs (savings in expenditure) associated with the measures, e.g. savings on N fertiliser expenditure. Costs and income accrued for each measure were annualised over the period (2024-2050) 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 = cost of measure in year t, $Benefit_t$ = Benefit in year t, r = the assumed 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, the net profitability will be achieved beyond the 2030 commitment period. The ESRI projections of personal consumption expenditure deflators (Table 1) for the period to 2050 were used to inflate the mitigation costs over the period to 2050.

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