An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture to 2030

Prepared by the Teagasc Gaseous Emission Working Group

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Contents

List of Figures

List of Tables

Executive Summary

This analysis quantifies the potential to abate national ammonia (NH_3) emissions up to 2030. This report is an updated marginal abatement cost curve (MACC) analysis where Teagasc has quantified the abatement potential of a range of ammonia mitigation measures, as well as their associated costs/benefits (see Lanigan et al. 2015 for previous analysis). The objective of this analysis is to quantify the extent and costs associated with meeting future ammonia emission targets that were negotiated as part of the amended Clean Air Policy Package.

The requirement to reduce ammonia emissions is urgent, both in terms of compliance with the National Emissions Ceilings Directive (NECD), and as a principal loss pathway for agricultural nitrogen (N). Improvement of N efficiency is a key focus for improving farm efficiency and sustainability as well as reducing the ammonia, nitrate and greenhouse gas (GHG) footprint of agriculture. This is particularly relevant in the context of the national strategies on the development of the agri-food sector: Food Wise 2025, Ag-food strategy 2030 and Ag-Climatise (currently under development) and the newly unveiled EU Farm to Fork Strategy, which is a part of the European Green Deal.

Under the baseline scenario (S1), agricultural ammonia emissions are projected to increase by 9% (without any mitigation) by 2030 relative to 2005 levels. While these increases are small in comparison to the targeted increase in agricultural output, they will provide a major challenge to meeting emissions targets, particularly as agriculture comprises over 99% of national emissions. The analysis presented in this report seeks to quantify the ammonia mitigation potential under likely uptake pathways.

This is not an exhaustive analysis of all mitigation measures, but represents an assessment of best available techniques, based on scientific, peer-reviewed research carried out by Teagasc and associated national and international research partners. Indeed, any future changes in the sector or in the national emission inventory calculations will require further analysis of the applicability of ammonia mitigation techniques, particularly in terms of housing and storage but also in the context of other reactive N[1] emissions. It should also be noted that some mitigation measures, particularly those related to nitrogen application to soils, could result in either *higher* greenhouse gas emissions or *higher* nitrate leaching.

Compared to a future where no mitigation measures are deployed to address emissions, by 2030 the average technical abatement[2] potential was estimated to be approximately 15.26 kt NH_3 at a net cost of €10.86 million per annum. However, it should be noted that the net cost (€10.86 million) is comprised of 6 measures that are cost negative (-€22.21 million) and

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[1] Reactive N is a term used for many N compounds supporting agricultural production but also leading to environmental losses. Reactive N species include chemical compounds such as ammonia (NH_3), nitrous oxide (N_2O) and nitrate ($NO3^-$).

[2] For the purpose of this document, technical abatement is defined as full implementation of the measures selected in this study. These measures are deemed to be currently feasible for implementation according to the prescribed pathways.

7 measures that are cost positive (€33.07) and that some of the cost negative measures are predicated on efficiency gains driven by best management practice adoption (e.g. liming and clover measures with associate chemical N reductions).

Amongst the thirteen mitigation measures selected for this analysis, 80% of the mitigation potential can be achieved by the full implementation of the mitigation pathways for protected urea and low emission slurry spreading (LESS) techniques for bovines.

It should be stressed that this is an assessment of the maximum abatement potential and realising this level of abatement in practice will be extremely challenging. Any increase in agricultural activity beyond the baseline scenario will increase absolute emissions. The level of mitigation achievable is based on the draft AgClimatise measures any delay or reduction in the uptake of these measures will reduce the mitigation achieved. It must also be ensured that all mitigation measures should, where possible, be synergistic with reductions in greenhouse gas emissions and N loss to water.

Glossary

Activity data	Data that quantify the scale of agricultural activities associated with emissions at a given moment in time. Activity data are expressed as absolute numbers (e.g. number of dairy cows, national fertiliser N usage) and typically change over time.
CLRTAP	The Convention on Long-Range Transboundary Air Pollution was the first international legally binding instrument to deal with problems of air pollution on a broad regional basis. It was signed in 1979 and entered into force in 1983. It has since been extended by eight specific protocols. These include the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone which covers ammonia emissions.
Emission factor	Established numbers that quantify the emissions associated with activity data (see above), and that are expressed as "emissions per activity unit", e.g. ammonia emissions per kg N applied. Generally, the values of emission coefficients do not change over time, unless more accurate/representative values are obtained by new research.
EPA	Environmental Protection Agency (Ireland)
EU	European Union
FAPRI-Ireland	Collaboration between Teagasc and the Food and Agricultural Policy Research Institute at the University of Missouri
GHG	Greenhouse Gas
Gothenburg Protocol	The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (known as the Multi-effect Protocol or the Gothenburg Protocol) is a multi-pollutant protocol designed to reduce acidification, eutrophication and ground-level ozone by setting emissions ceilings for sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia to be met by 2010, 2020 and 2030.
kt	Kiloton (1,000,000 kg)
LESS	Low Emission Slurry Spreading
MACC	Marginal Abatement Cost Curve

M€	Million euro
N	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NECD	National Emissions Ceilings Directive
TAN	Total Ammoniacal Nitrogen, the proportion of mineral N in animal excreta
UNECE	United Nations Economic Commission for Europe
Protected urea	Urea coated with a urease inhibitors such as N-(n-butyl) thiophosphoric triamide (NBPT), N-(n-propyl)-thiophosphoric triamide (NPPT) or N-(2-Nitrophenyl) phosphoric triamide (2-NPT). This coating inhibits hydrolysis of urea to ammonium (NH4+), which is then susceptible to ammonia (NH_3) loss.

Acknowledgements

We gratefully thank Bernard Hyde (EPA) for providing national ammonia emission inventory data.

1 Background

1.1 Legislation Framework and Ireland's Emission Reduction Commitments

The United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen estimates that approximately 80% of nitrogen is lost from agriculture through leaching and run-off of nitrate or organic nitrogen and gaseous emissions of ammonia and nitrogen oxides to air (UNECE, 2018). Ammonia (NH_3) is an air pollutant contributing to eutrophication and acidification of terrestrial and aquatic ecosystems, and an indirect source of a potent greenhouse gas nitrous oxide (Sutton et al., 1992).

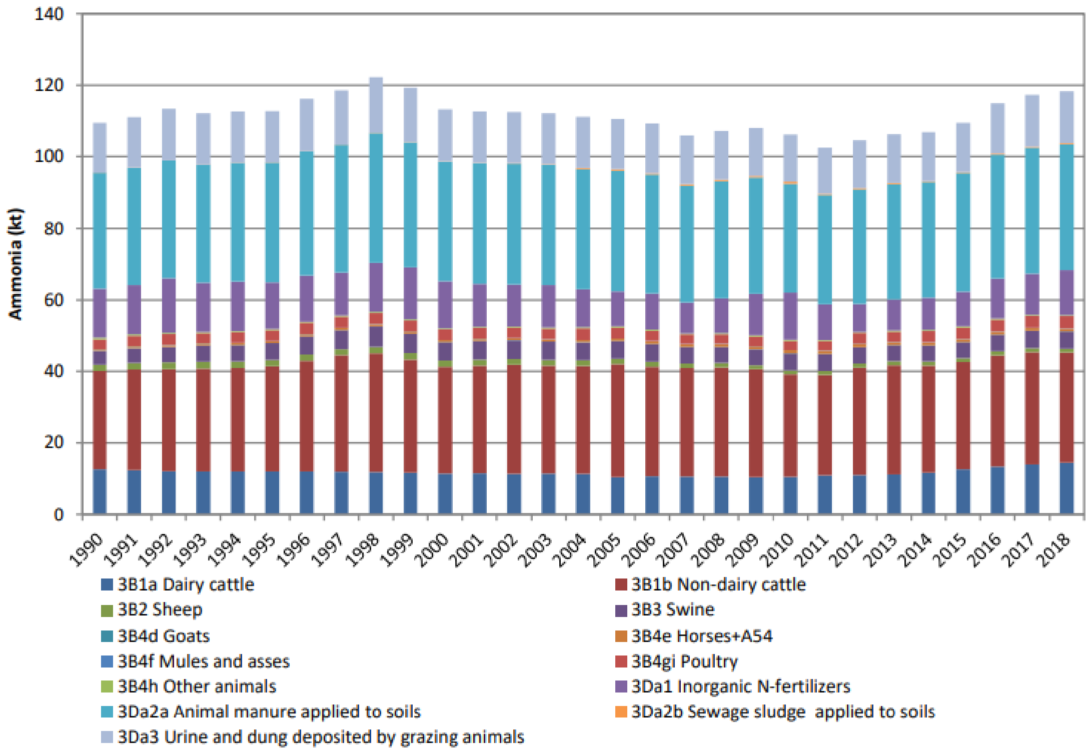
Ireland is a Party to the Convention on Long-Range Transboundary Air Pollution (CLRTAP), which targets the control and reduction of emissions of certain transboundary air pollutants (UNECE, 1999). The Convention includes a number of Protocols dealing with specific measures to reduce emission of air pollutants, such as Gothenburg Protocol responsible for ammonia. European countries committed to reduce emissions of NH_3 under the European Union's National Emissions Ceiling Directive (NECD; European Commission, 2016), which implements the Gothenburg targets for EU Member States. EU Member States have been allocated emissions ceilings through the NECD. For Ireland an annual emissions ceiling of 116 kilotonnes NH_3 was allocated under Article 4 of the NEC Directive 2001/81/EC, which continued to apply until the 31st of December 2019. This was a fixed value target. Beginning in 2020, Article 4(1) of Directive 2016/2284 and Annex II set out new national emission reduction commitments for each EU Member State for the years 2020 to 2029 and 2030 onwards. These new reduction targets have to be achieved relative to the levels of emissions in 2005. These targets are percentage reductions in comparison to the latest national emission inventory estimate for 2005. For Ireland these reduction commitments are as follows:

- 1% reduction relative to 2005, currently estimated at 112.13 kT NH_3 to be achieved in the 2020 commitment period
- 5% reduction relative to 2005, currently estimated at 107.5 kT NH_3 to be achieved in the 2030 commitment period

1.2 Irish Ammonia Emissions Profile

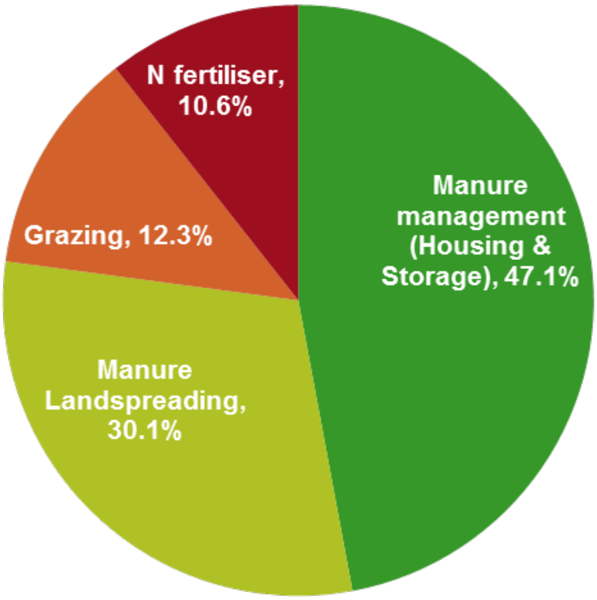
Ammonia emissions have been steadily increasing in Ireland since 2011 (Figure 1.1, EPA, 2020) as a result of increasing agricultural activity, with the first exceedance of the emission ceiling reported in 2016, and subsequently in 2017 and 2018. Moreover, emissions are projected to increase further in the new commitment periods (EPA, 2020), therefore the implementation of abatement strategies are urgently required.

Figure 1.1: Emissions Trends for Irish Agriculture in 1990-2017 (from EPA, 2020).



Nearly all of Irish ammonia emissions (99.2 %) originate from agricultural activities, 89.4 % from manures and the remaining 10.6 % from synthetic fertilisers and transport (Figure 1.2, adapted from EPA, 2020). Irish agriculture is dominated by pastoral bovine livestock production, with approximately 90 % of the utilisable agricultural area in Ireland comprised of permanent grassland (CSO, 2019). This dictates the farming system and also defines to a large extent the ammonia abatement practices available.

Figure 1.2*:* Breakdown of Agricultural Sources of Ammonia Emissions in Ireland (based on EPA, 2020).



Typically livestock in Ireland are fed a grass based diet (grazed grass and grass silage) and spend about 60% of their time on pasture. As a result N excreted on pasture accounts for 61% of total N excretion, compared to 8% for Denmark, 10.6% for Germany and 13.6% for the Netherlands (UNECE, 2017).

This has resulted in comparatively low Irish national emissions both in absolute terms and in terms of applied agricultural N (8.8%) lost as ammonia, comparing favourably with other large EU agricultural producers. However, this high proportion of grazing results not only in low existing ammonia emissions, but a somewhat challenging task to achieve further ammonia abatement.

1.3 Context of the Analysis of Ammonia Abatement Potentials

In 2015, Teagasc prepared the first analysis of the cost of the abatement of ammonia emissions in Irish Agriculture to 2030 (Lanigan et al., 2015) outlining possible measures to reduce ammonia emissions and associated abatement benefits and projected costs of adoption. In 2017, Teagasc made a submission to the Department of Communications, Climate Action & the Environment in response to the public consultation on the National Clean Air Strategy (Lanigan et al, 2017), in the context of ammonia abatement. Most recently, in 2019 Teagasc made a submission to the Department of Communications, Climate Action and Environment in response to the public consultation on the National Air Pollution Control Programme, specifically focused on ammonia abatement in agriculture (Krol et al., 2019). Lately, a need arose for an updated analysis of ammonia mitigation potential in Irish agriculture, in order to reflect recent developments at a national level, such as:

- Policy: recent changes introduced by the Department of Agriculture, Food and the Marine (DAFM) regarding nitrogen management on derogation[1] farms and the use of low emission slurry spreading techniques, the Climate Action Plan 2019 (DCCAE, 2019) outlining greenhouse gas (GHG) mitigation in agriculture, which will have an impact on ammonia mitigation and lastly, changes proposed during the public consultation and workshops for the development of the DAFM's AgClimatise strategy.

- Activity Data: Inclusion of the most recent projected agricultural activity scenarios. These projections are generated from the FAPRI-Ireland Partial Equilibrium Model of the Irish agricultural economy (Donnellan & Hanrahan, 2019) and are produced by the Rural Economy & Development Programme of Teagasc. This data is also provided to the Environmental Protection Agency for inventory compilation purposes under a Memorandum of Understanding.

- National emission inventory: the national emission inventory outlining ammonia emissions in a given year is compiled by the Environmental Protection Agency (EPA) with the use of the best available activity data and emission factors. Since the previous analysis, the national emission inventory has updated emission factors for synthetic fertilisers, housing and storage of manures and updated the proportion of covered/uncovered stores in the bovine and pig sub-sectors.

- Scientific advancement: Introduction of new ammonia mitigation measures into the current analysis in order to reflect advancement in scientific research. The analysis includes reduction in crude protein in dairy cows diets, the use of slurry amendments and acidifiers in storage and at landspreading for bovine and pig slurry and improved nutrient management efficiency through the use of liming and clover.

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[1] A nitrates derogation in Ireland allows farmers to farm at higher stocking rates, above 170 kg livestock of organic nitrogen ha^{-1}, subject to additional conditions designed to protection of the environment. Without a derogation a farmer must not exceed 2 dairy cows per ha^{-1} with a derogation but can farm at almost 3 cows per ha^{-1}. The derogation is availed of by almost 7,000 intensively stocked farmers in 2018 (DAFM, 2020).

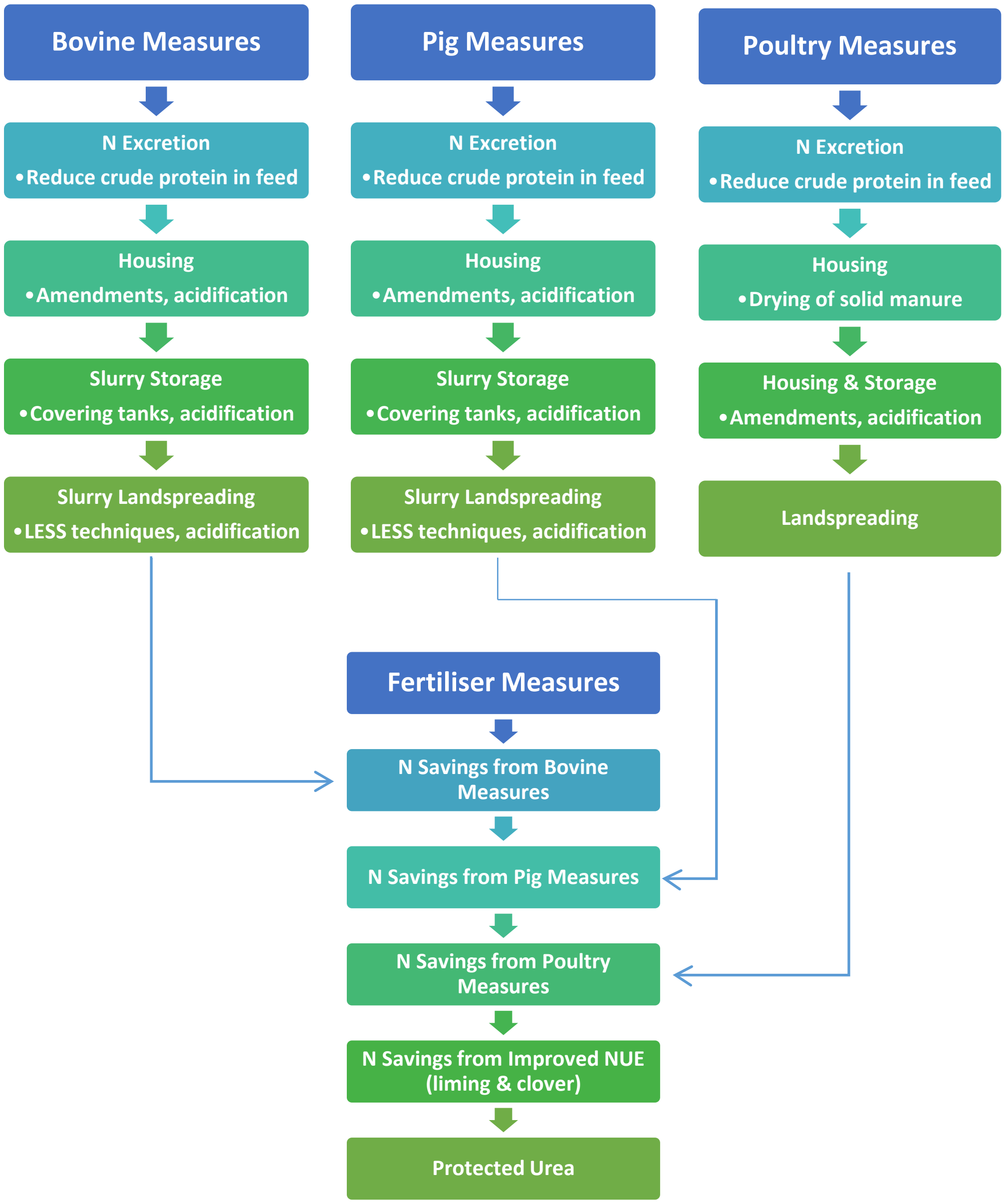
1.4 N Flow Framework

Ammonia is emitted in agricultural systems at different stages, as organic material and N flows through the systems from fertilisation to agricultural products. This flow can be described as the N flow model proposed in the EMEP/EEA Emission Inventory Guidelines, the latest iteration of which was in 2019. Therefore, ammonia abatement measures are interdependent and should be applied in a logical sequence to minimize overall emissions in the system. Abatement options for ammonia reduction at the various stages of livestock N flow through the system are interdependent, and combinations of measures are not simply additive in terms of their combined emissions reduction capacity (since mitigation at a higher level, may affect the volume of N available for mitigation at a subsequent stage in the N flow). Applying abatement techniques upstream may lead to increased emissions downstream, as more nitrogen is retained in the system, e.g. slurry additives reduce ammonia losses during storage leading to preservation of nitrogen, if the material is then land spread using splash plate techniques, ammonia emissions can increase based on the increased nitrogen content of the slurry spread (as illustrated in Figure 1.3). Conversely, if N is conserved throughout the manure management chain and even prior to that, through reduced crude protein intake in animal diet, this will ultimately lower ammonia emissions throughout the system and by improving nutrient use efficiency of organic manures, will lead to reduced need for synthetic fertiliser. Reduced application of chemical N will then in turn lower emissions associated with synthetic fertiliser use.

Controlling ammonia emissions from the application of manures to land is particularly important, because a) these are generally a large component of total livestock emissions and b) land application is the last stage of manure management chain. Without abatement at this stage, much of the benefit of the abatement achieved during housing and storage, which is often more costly, may be undone. Emissions of ammonia from the intensive pig and poultry sectors are significantly lower than from cattle, and are addressed within current Integrated Pollution Prevention and Control (IPPC) legislation and controls (Anon, 2003). Moreover, ammonia abatement measures for these sectors have recently been specified in the best available techniques (BAT) conclusions document (European Commission, 2017). Therefore, there is greater urgency required in increasing the understanding of how emissions are generated and how abatement strategies can be employed on bovine and tillage farms.

In terms of pollution swapping, strategies which reduce emissions from one reactive N loss pathway could lead to an increase in loss via another pathway (greenhouse gas nitrous oxide (N_2O); or leached nitrate). The injection of slurry has been shown to decrease ammonia by 70%-90%, but can increase N_2O emissions (Wulf et al. 2002). Similarly, drying manure can reduce ammonia, but substantially increase N_2O emissions (Amon et al. 2006). These antagonistic relationships between strategies to reduce emissions of different gases ideally need to be considered within an integrated analytic framework. Failing that the trade-offs need to be considered when designing policy measures to incentivise GHG and/or ammonia abatement. In the current analysis all the mitigation pathways were implemented in the order of appearing in the N flow framework to best account for any interdependencies between individual measures and this is reflected in the results of this study.

Figure 1.3: Conceptual N Flow Framework Used in MACC Analysis



2 Projections of Activity Data

Ammonia emissions are calculated based on a range of emission factors applied to relevant activity data. Emission factors are determined at national emission inventory level, while activity data are based on projections from the FAPRI-Ireland Partial Equilibrium Model of the Irish agricultural economy (Donnellan & Hanrahan, 2019). Three alternative scenarios are generated by the FAPRI-Ireland model, a Baseline (S1), Low (S2) and High (S3) activity level scenarios for provision to the Environmental Protection Agency for scenario modelling purposes. These scenarios were developed for sensitivity purposes in the reporting of GHG emissions under the Monitoring mechanism Regulation and reflect some of the uncertainty concerning future levels of agricultural activity in Ireland over the period to 2030. The activity data under S1 to S3 scenarios (as set out above) is included in the national inventory accounting framework (Duffy et al., 2020) to estimate aggregate NH3 emission for Ireland as reported by the EPA under the EU NEC Directive.

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

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

Three alternative scenarios have been generated by the FAPRI-Ireland model, a Baseline (S1), Low (S2) and High (S3) activity level scenarios (Donnellan and Hanrahan, 2019). These scenarios were developed for sensitivity purposes in the reporting of GHG emissions under the Monitoring mechanism Regulation and reflect some of the uncertainty concerning future levels of agricultural activity in Ireland over the period to 2030. The macroeconomic aggregates taken from the ESRI COSMO model and the international agricultural commodity and input prices taken from the FAPRI-EU model are unchanged across the three scenarios, see Donnellan and Hanrahan (2019) for more detail on these projections and Donnellan and Hanrahan (2006), Binfield et al. (2008), Donnellan and Hanrahan (2006) and Hanrahan (2001) on the FAPRI-Ireland model structure and functioning.

The key driver of agricultural NH_3 emissions in Ireland is bovine activity levels. The differences between the three scenarios primarily relate to differences in dairy and beef cow numbers, associated cattle progeny, land use, use of fertilisers and other inputs. It is important to emphasise that the projections under each of the three scenarios are not forecasts. The projections are based on a set of differing assumptions concerning future policy and market conditions. The different scenarios are presented as an aid to understanding that there is a range of possible different future agricultural activity outcomes in the presence of policy and market uncertainty (see Table 2.1 for further details).

Because of the uncertainty concerning future economic and policy variables such as agricultural prices, the level of support for agriculture and the presence of trade tariffs, it is not possible to know with certainty future level of agricultural activities and by extension future levels of NH_3 emissions from agriculture. The key uncertainties facing Irish agriculture include the impact of Brexit and the impact of the ongoing CAP reform process as well as the impact of the unfolding COVID-19 pandemic and its economic ramifications.

How Brexit is dealt with in the scenarios is summarised in Table 1. Given the ongoing, and as of yet incomplete nature of the CAP reform process, it has not been possible at this stage to address the impact of potential EU CAP reform outcomes. Irish environmental policy, particularly as it applies directly to agriculture, is undergoing change. Future policy developments may introduce new constraints on agricultural activity; no attempt has been made to incorporate such constraints in the agricultural activity projections underling this analysis.

Under Scenario 2 a hard Brexit leads to the imposition of tariff barriers on EU-UK trade as outlined in Table 2.1. These tariffs (taxes on trade) dramatically reduce Irish agri-food exports to the UK and Irish imports of agri-food products from the UK. The loss of preferential market access to the UK market leads to a diversion of Irish agricultural exports to EU27 markets. Irish agricultural commodity prices decline significantly. As outlined in Hanrahan and Donnellan (2019) and Hanrahan, Donnellan and Thorne (2019a, 2019b) the most impacted sub-sectors of Irish agriculture are those with a high dependence on the UK market, which are not competitive at world prices and where farm incomes have a high degree of dependence on CAP direct payments. In an Irish context he beef sector is expected to be the most severely affected, the international price competitiveness of Irish dairy exports and relatively low levels of dependence on the UK market are expected to mitigate the negative impact of Brexit on the Irish dairy sector.

There remains uncertainty concerning the future evolution of the Irish bovine sector. The ongoing COVID-19 crisis and the recession that has ensued highlight the continuing uncertainty regarding projections of economic aggregates and agricultural activity levels. Recent growth in dairy cow numbers has to date been coincided with contraction in the beef cow herd and continues the well-established historical pattern of a negative correlation between growth in the dairy and suckler cow herds. One of the scenarios (S3) examines the impact of deviations from this relationship, i.e. where continued growth in the dairy cow herd occurs in tandem with stability in the beef cow herd. Macroeconomic assumptions used (currency exchange rates, GDP growth and inflation rates) do not vary across the three scenarios analysed.

Table 2.1: Summary of Scenarios Analysed

Scenario	Policy	Policy assumption
S1 (Baseline activity level)	CAP	In spite of the UK departure from the EU, the CAP continues to 2030 as currently structured. There is no change in total CAP budget or Ireland's share of same.
	Brexit & Trade	A soft Brexit occurs with the UK and EU trade relationship continuing to de facto be equivalent to UK membership of the Single Market. There are assumed to be no changes in EU trade relationships with other third countries.
S2 (Low activity level)	CAP	In spite of the UK departure from the EU, the CAP continues to 2030 as currently structured. There is no change in total CAP budget or Ireland's share of same.
	Brexit & Trade	A hard Brexit occurs and the UK applies the announced "temporary UK tariff Schedule" for all of the period 2020-2030. The EU applies Most Favoured Nation (MFN) tariffs to imports from the UK. The introduction of tariffs on EU-UK trade leads to changes in trade flows, agricultural activity levels, agricultural production, and domestic use and agricultural commodity prices. There are assumed to be no changes in EU trade relationships with other third countries.
S3 (High activity level)	CAP	In spite of the UK departure from the EU, the CAP continues to 2030 as currently structured. There is no change in total CAP budget or Ireland's share of same. A greater share of Ireland's CAP budget is coupled to beef cow farming activity (suckler cow payments are reintroduced) and farm gate milk prices in Ireland are assumed to be higher than under S1.
	Brexit & Trade	A soft Brexit occurs but the UK and EU trade relationship continuing to de facto be equivalent to UK membership of the Single Market. There are assumed to be no changes in EU trade relationships with other third countries

S1 Baseline

Under the Baseline scenario (S1), dairy cow numbers are projected to increase, reflecting the continuing profitability of dairy production in Ireland. Dairy cow numbers in 2030 reach 1.636m. This represents a 15% increase relative to 2018. In contrast, the continuing low levels of profitability of beef cow production systems is reflected in a projected contraction of the beef cow population. Beef cow numbers in 2030 are projected to decline to 0.76m. This represents a 25% decrease relative to 2018.

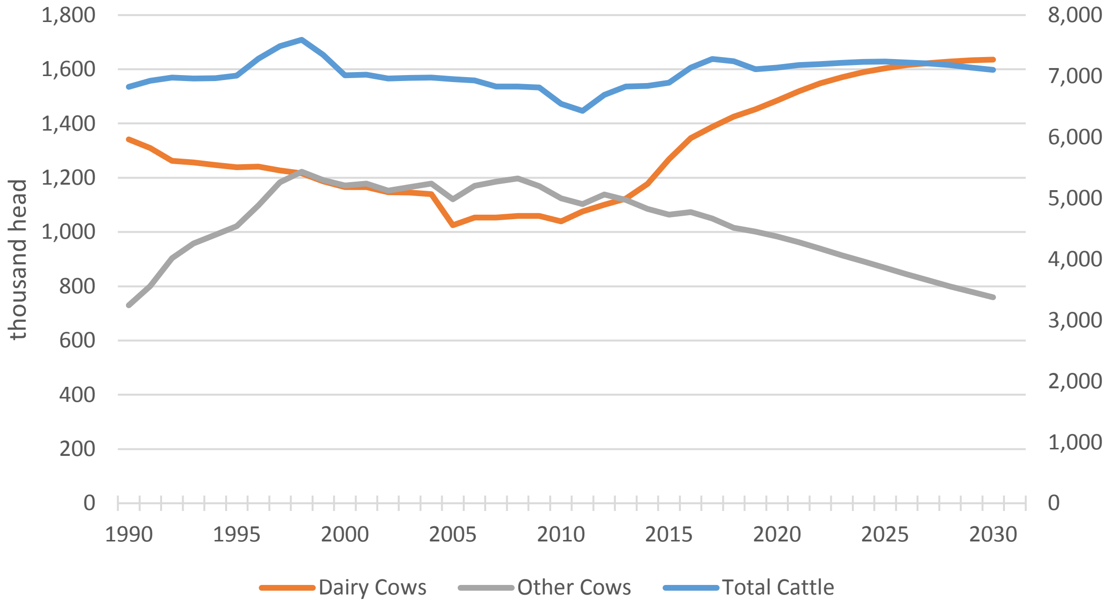
The overall cattle population is determined by these two key breeding inventories and by the level of live exports of cattle from Ireland. Total cattle population under the base case is projected to increase over the period to 2025. Thereafter they decrease modestly, so that by 2030 total cattle numbers are marginally lower than in 2018. Total cattle population in 2030 is projected to be 7.1m. This represents a 2% decrease relative to 2018.

Even though total cattle population is relatively stable over the projection period, projected growth in dairy cow numbers and contraction in beef cow numbers leads to a change in the composition of the Irish bovine inventory and in the intensity of grassland use. Dairy production systems operate at a higher stocking rate than beef production systems and this higher stocking rate is reflected in higher projected use of nitrogen fertiliser per hectare and in total aggregate nitrogen fertiliser use by the Irish agricultural sector. Total nitrogen fertiliser use in 2030 is projected to be 398,000 tonnes. This represents a 3% decrease relative to 2018. However, it should be noted that due to adverse weather in 2018, fertiliser use in that year was particularly elevated (fertiliser use in 2030 is projected to be 7% higher than the average level for the period 2016-2018). .

Under the baseline, Irish ewe and total sheep numbers are projected to contract over the period to 2030. By 2030 total Irish sheep numbers are projected to decline to 4.65m. This represents a 10% decrease relative to 2018. This contraction reflects the low profitability of this farming activity on a per hectare basis.

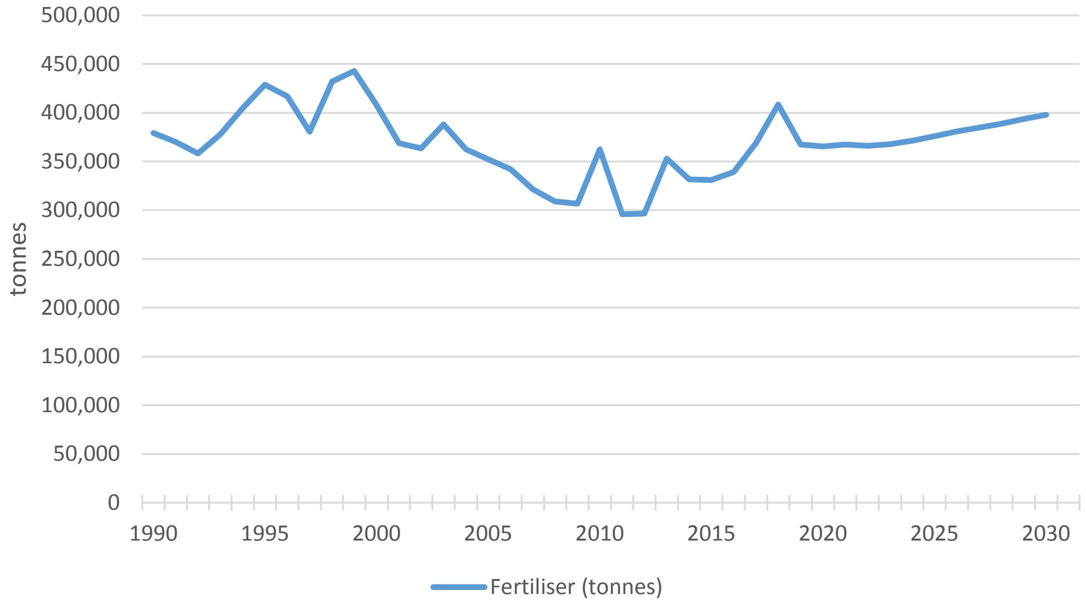
Under the baseline the total crop land area is projected to continue to decline due to the higher level of profits per hectare in dairy farming as compared to tillage farming. By 2030 total cereal area harvested in Ireland is projected to decline to 223,000 hectares. This represents a 14% decrease relative to 2018.

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



Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model.

Figure 2.2: Total Nitrogen Fertiliser Sales 1990-2030 (Base Case S1)



Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model.

S2 Low Activity Scenario (Hard Brexit)

Under the Low activity scenario (S2) a hard Brexit is assumed to take place with EU-UK trade relationship governed by the EU Third County applied tariff schedule and the announced UK temporary tariff schedule.

The imposition of tariffs by the UK on imports of agricultural goods form the EU27 (including Ireland) leads to a dramatic reduction in the UK demand for Irish agri-food exports. Tariffs are taxes that increase the price of Irish exports to UK consumers; the magnitude of the tariffs imposed are large enough, given the elasticity of UK import demand, to effectively suppress UK demand for many Irish agri-food exports (Hanrahan, Donnellan and Thorne, 2018 and Donnellan, Hanrahan and Thorne 2019a, 2019b). Irish agri-food exports that under S1 and S3 are shipped to the UK are diverted to EU 27 and world markets and the farm gate price of most agricultural commodities in Ireland is lower than under both S1 and S3. As noted earlier the most negatively affected sub-sector of Irish agriculture is likely to be the beef sector, the Irish dairy sector, due to its lower dependence on the UK market and international price competitiveness, is less negatively affected by a hard Brexit.

Under the S2 scenario, Irish dairy cow numbers are still projected to increase relative to observed levels in 2018. This increase reflects the continuing profitability of dairy production in Ireland in spite of the assumed hard Brexit. Dairy cow numbers in 2030, under S2, are projected to reach 1.562 m. This represents a 10% increase relative to 2018. However, the projected population for 2030 represents a decline relative to the projected population for 2030 under the Base Case (S1).

Under a hard Brexit the Irish beef sector is the most exposed of Ireland’s major agricultural sub-sectors. Significantly lower levels of profitability that arise due to reduced beef prices lead to an accelerated contraction of the Irish beef cow herd. Under the Low activity scenario (S2) beef cow numbers in 2030 are projected to decline to 0.686 m. This represents a 32% decrease relative to 2018.

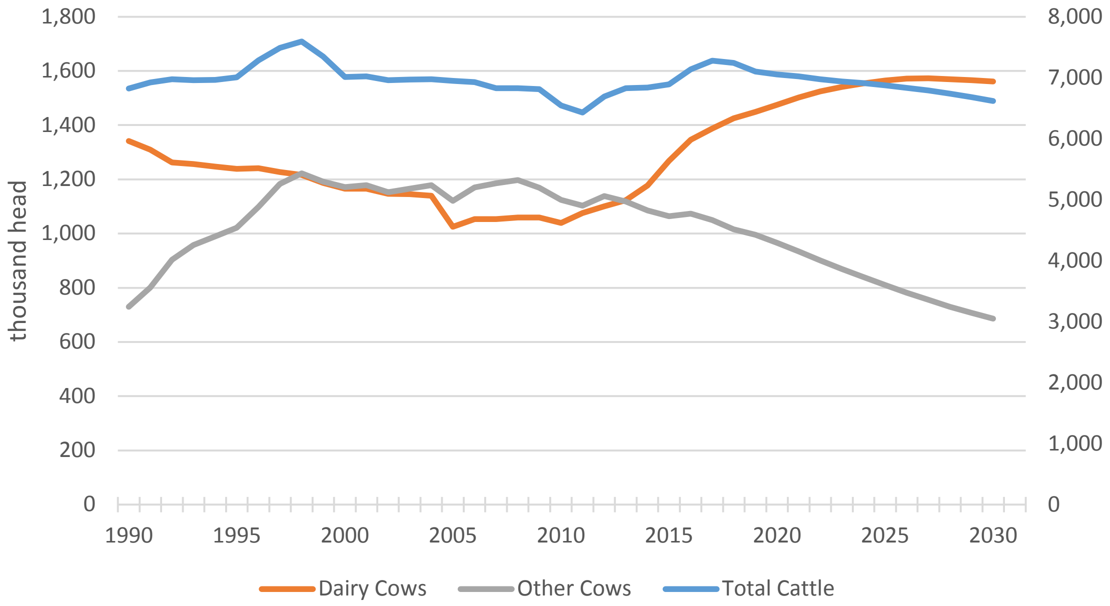
Under the Low activity scenario the total cattle population is projected to decline over the period. The Brexit driven contraction in beef cow numbers is sufficient to offset continued growth in dairy cow inventories. Total cattle population in 2030 is 6.618 m. This represents a 9% decrease relative to 2018.

Under S2, the contraction in beef cow numbers is more significant than under S1. Even though the total cattle population is falling, the dairy share of this population is increasing and the higher stocking rate on dairy farms offsets declining stocking rates on beef farms. While total use of nitrogen declines initially, it recovers over the period 2025 to 2030. In 2030 the total use of nitrogen is 370,000 tonnes. This represents a 9% decrease relative to 2018. It should be noted that due to adverse weather in 2018, fertiliser use in that calendar year was particularly elevated.

Under the Low activity scenario, the introduction of tariffs on EU-UK trade leads to a reduction in the exports of lamb from the UK to other EU markets. This projected reduction in supplies to the EU market is reflected in an increase in prices paid to Irish sheep farmers as European demand increases for Irish lamb. The higher price for lamb creates an incentive for farmers to add ewes and the total breeding population and overall number of sheep in Ireland is projected to increase over the period 2020 to 2030. In 2030 Irish total sheep numbers are projected to increase to 5.316 m. This represents a 3% increase relative to 2018.

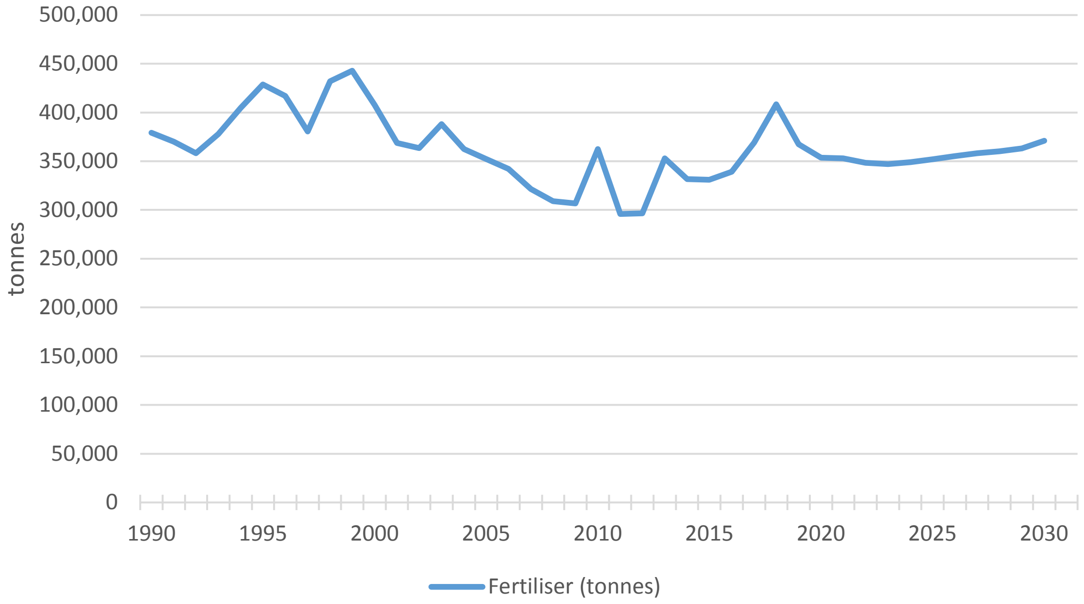
In the Low activity scenario total crop land is projected to decline more slowly than under S1. Brexit leads to slightly higher cereal prices in Ireland, as the introduction of tariffs on Irish cereal imports from the UK leads to higher Irish prices. By 2030 total cereal area harvested in Ireland declines to 241,000 hectares. This represents an 8% decrease relative to 2018.

Figure 2.3: Total Cattle, Dairy and Other Cow Populations 1990-2030 (Low Scenario S2)



Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model.

Figure 2.4: Total Nitrogen Fertiliser (as nutrient) Sales 1990-2030 (Low Scenario S2)



Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model.

S3 High Activity Scenario (Stronger Growth in Agricultural Activity Levels)

The future evolution of the Irish bovine population is uncertain. Heretofore growth in the dairy cow numbers has been accompanied by contraction in the beef cow herd, the two activities compete for agricultural land use (increases in dairy cow numbers are associated with reductions in beef cow numbers), while growth in the dairy cow herd also leads to an increase in the supply of calves that other things equal erodes the profitability of suckler cow farming. This scenario examines the consequences of departures from this well established historical relationship, with continued growth in the dairy herd accompanied by a stable, rather than a contracting beef cow herd. Under the High activity scenario (S3) the allocation of Ireland's CAP budget is assumed to change from 2020 onwards to provide additional coupled support to beef cow numbers. These coupled direct payments augment the economic incentive to maintain suckler cows and lead to suckler cow numbers in 2030 that are 20% higher under S3 than under S1. Irish farm gate milk prices are also assumed to be higher than under the Baseline by approximately 10%. These two assumptions are used to generate a larger dairy and beef cow population than under the other two scenarios analysed (S1 and S2).

Under S3, with stronger milk prices, Irish dairy cow numbers are projected to increase relative to 2019 levels. Dairy cow numbers in 2030, under S3, are projected to reach 1.738 m. This represents a 22% increase relative to 2018. This represents a stronger increase relative to the population number projected under the Base Case (S1).

Under the High activity scenario (S3) the provision of coupled direct payments from 2020 slows the projected decline in the Irish beef cow inventory. By 2030, under S3, Irish beef cow numbers reach 0.909 m. This represents a 10% decrease relative to 2018.

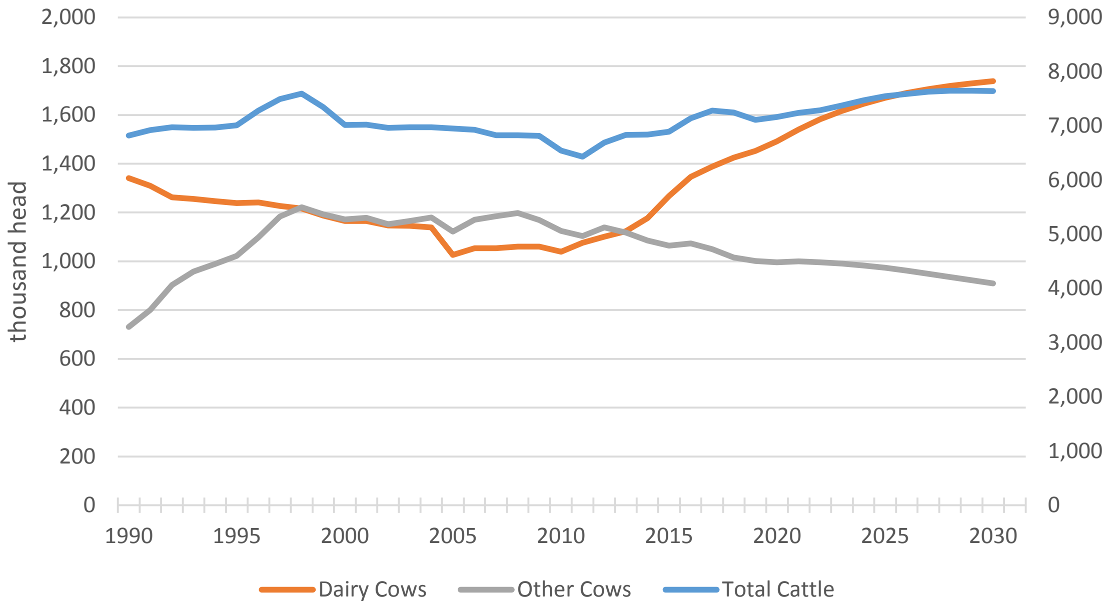
Under the High activity scenario, total cattle Inventories are projected to increase over the period to 2030. The increase in dairy cow inventories is not offset by the projected decrease in beef cow inventories. By 2030 projected total cattle inventories are 7.64 m. This represents a 5% increase relative to 2018.

Under S3, the modest projected contraction in beef cow numbers is more than offset by a strong increase in dairy cow numbers. 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 2030. In 2030 the total use of nitrogen fertiliser is projected to be 431,000 tonnes. This represents a 6% increase relative to 2018. It should be noted that due to adverse weather in 2018, fertiliser use in that calendar year was particularly elevated

Under the High activity scenario Irish ewe and total sheep numbers are projected to contract over the period to 2030. By 2030 Irish total sheep numbers are projected to decline to 4.48 m. This represents a 13% decrease relative to 2018. This contraction reflects the low profitability of this farming activity on a per hectare basis and the relative stability of the Irish beef cow herd under S3.

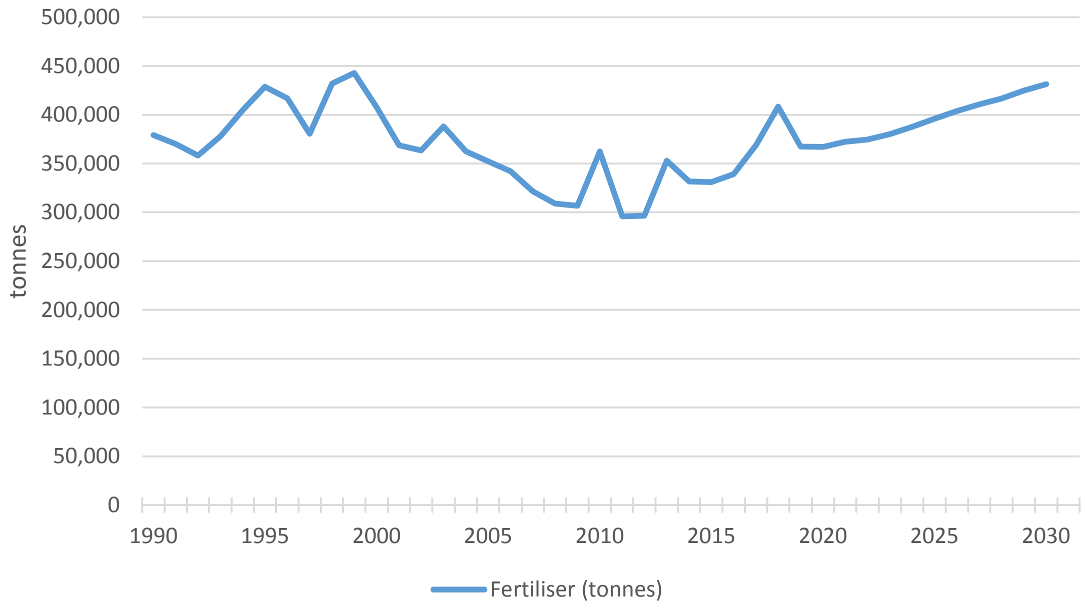
In the High activity scenario total crop land area is projected to decline over the period to 2030. The higher profitability of land use in dairy production systems leads to a shift of land from tillage to grassland use. By 2030 total cereal area harvested in Ireland declines to 216,000 hectares. This represents a 17% decrease relative to 2018.

Figure 2.5: Total Cattle, Dairy and Other Cow Populations 1990-2030 (High Scenario S3)



Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model.

Figure 2.6: Total Nitrogen Fertiliser (as nutrient) Sales 1990-2030 (High Scenario S3)

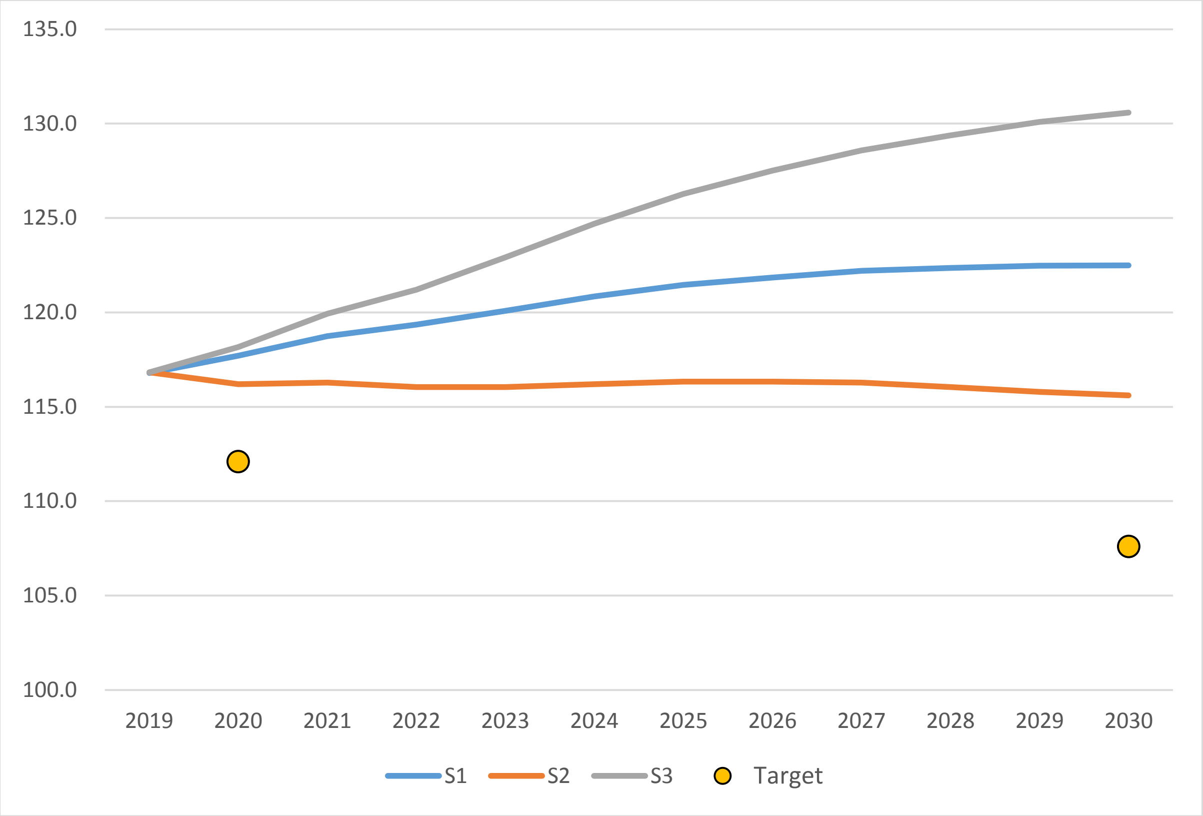


Source: Historical data EPA, Projections from 2019 FAPRI-Ireland Model

2.1 Aggregate Emission under Different Scenarios to 2030

Figure 2.7 below outlines the aggregate emissions using the EPA national emission inventory model (Duffy et al., 2020) for the agricultural sector in Ireland under the three activity level scenarios without mitigation. Under the S1 scenario aggregate emissions reach 123.8 kilotonnes, whereas under scenarios S2 and S3 emissions totalled 116.9 and 132 kilotonnes of NH_3 respectively. The yellow points in Figure 2.7 reflect the ammonia emission targets as set down under the NECD.

Figure 2.7: Total Aggregate NH_3 Emissions under S1, S2 & S3 Scenarios with no Mitigation (kilotonnes)



3 Abatement of Ammonia Emissions – Framework and Summary Results

3.1 What is a Marginal Abatement Cost Curve and How to Use it?

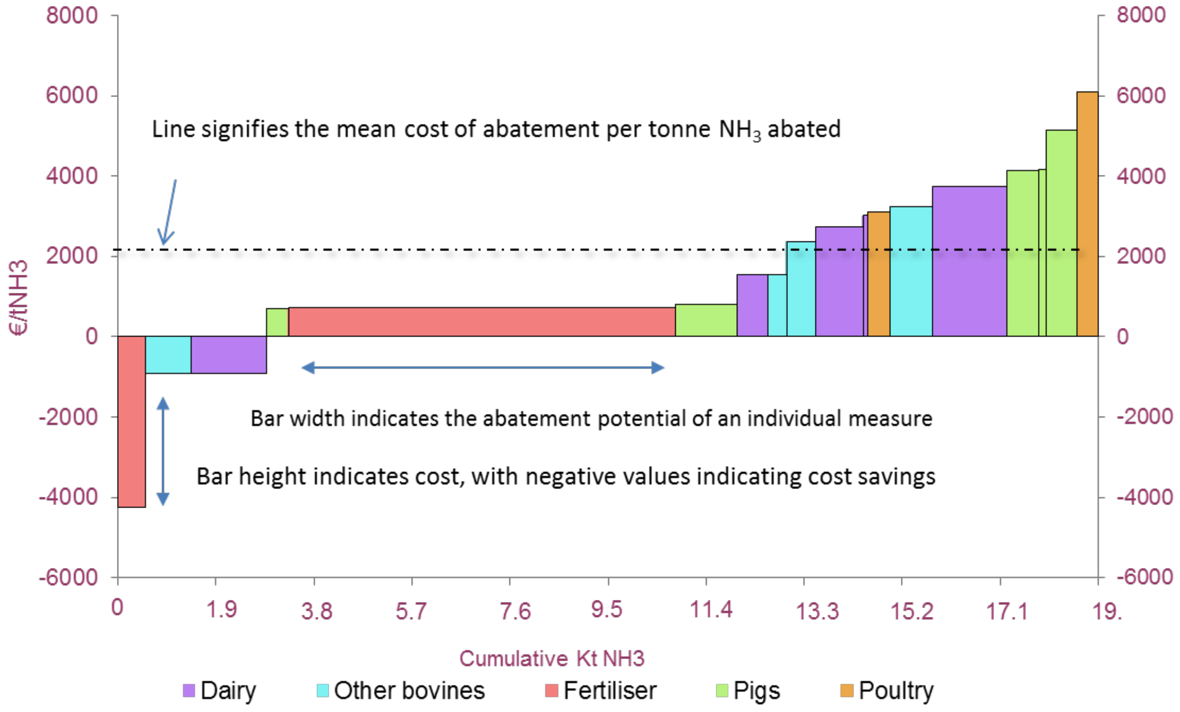
A Marginal Abatement Cost Curve (MACC) is a graph that represents the abatement potential of ammonia mitigation measures, and the relative costs associated with each of these measures.

A MACC provides two elements of information:

1. It ranks (on the basis of euro per tonne or kg of ammonia abated) the mitigation measures from most cost-beneficial measures (i.e., measures that not only reduce ammonia emissions, but also save money) to cost prohibitive measures (i.e., measures that save ammonia emissions, but which are relatively expensive). Cost-beneficial measures have a "negative cost" per tonne or kg of ammonia abated, and are represented on the graph below the x-axis, on the left-hand side of the curve. Cost-prohibitive measures are above the x-axis, on the right-hand side of the curve.

2. It visualises the magnitude of the abatement potential of each measure in kt of NH_3, as indicated by the width of the bar.

Figure 3.1: Histogram of Abatement Potential and Net Marginal Costs Associated with Individual Measures.



3.2 Selection of Measures

Mitigation measures for ammonia abatement considered for this report were chosen based on these reported in the international literature (Misselbrook et al. 2004, Reis et al. 2015, Bittman et al. 2014). The Guidance Document on Preventing and Abating Ammonia Emissions from Agricultural Sources was produced 'to provide guidance to the Parties to the Convention in identifying ammonia control measures for reducing emissions from agriculture' (Reis et al. 2015). These guidelines divide abatement options into three categories:

Category 1: Techniques that have been well researched, considered to be practical or likely practical, and there are robust quantitative data on their abatement efficiency, at least on the experimental scale;

Category 2: Techniques and strategies which are promising, but where research has not yet produced robust abatement estimates and therefore reliable emission factors cannot be derived, or where it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of an ammonia abatement strategy, depending on local circumstances;

Category 3: Techniques and strategies which have not yet been shown to be effective or are likely to be excluded on practical grounds.

This analysis focussed primarily on Category 1 measures. However, where Irish studies indicated differences in absolute abatement potential of a particular measure, as well as their associated costs/benefits compared to the Guidance document, the national values were instead used.

Many housing/storage options in the UNECE guidance document (UNECE, 2018) were not considered here, primarily due to configuration of Irish animal housing systems (over-slatted tanks), which make many technologies impractical in an Irish context. In some cases, where there was no Irish specific information, it was decided on a case by case basis whether it was appropriate to adopt the abatement potential, or costs from other countries as set out in the description of measures in section 4. Therefore, for the MACC presented in this report, individual measures were selected and included on the basis of the following criteria:

- Measures must be applicable to farming systems common in Ireland;

- Scientific data, from completed research, must be available on the abatement potential of each measure, as well as the cost;

- For each measure, activity data (actual and projections) must be available to assess the total national abatement potential and associated cost/benefit.

3.3 Assessment of Ammonia Mitigation Potential on S1 Activity Level.

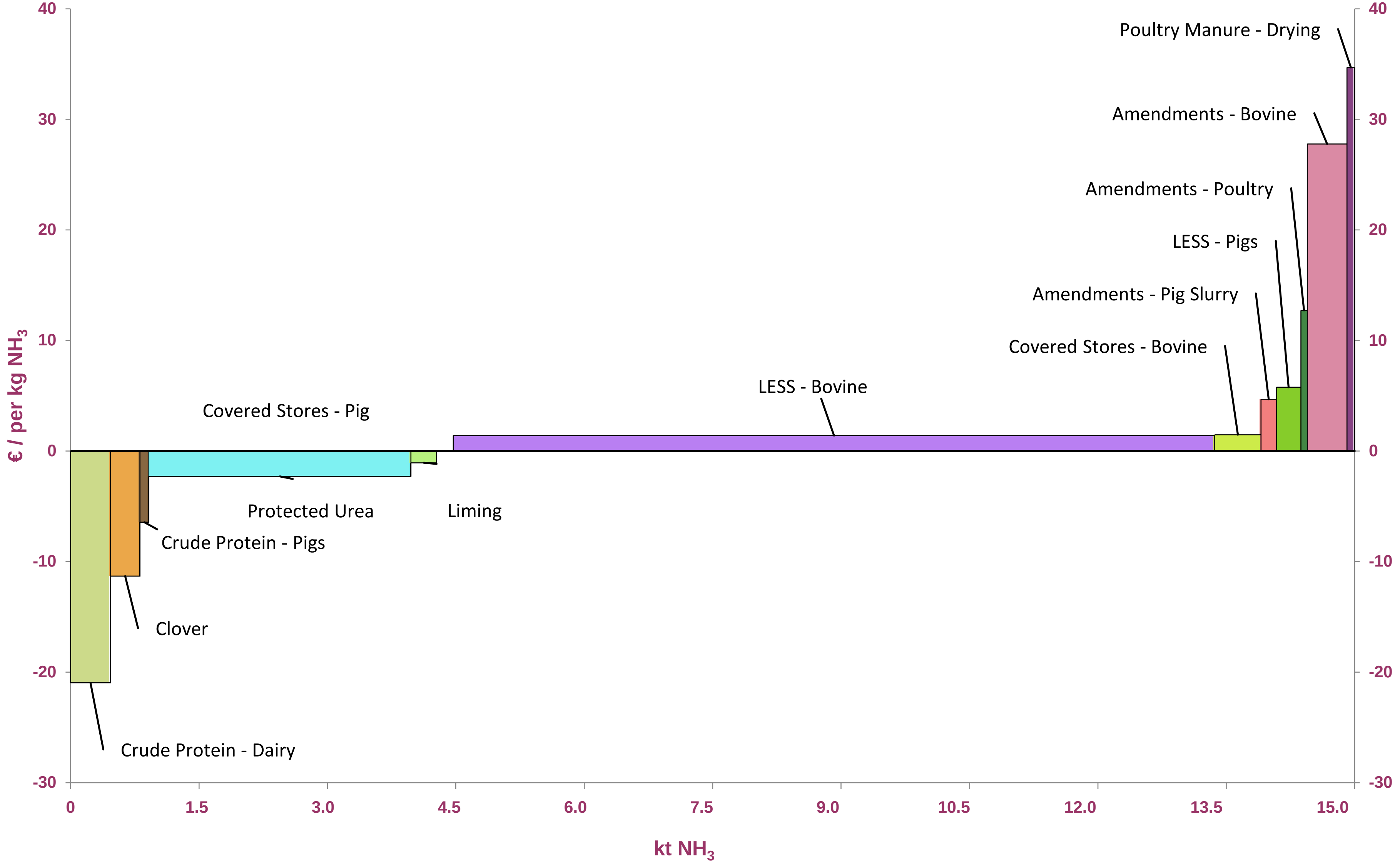
For all the mitigation measures assessed in this report, the S1 scenario is used as the baseline for analysis. The abatement potential and associated costs of the 13 individual measures identified in this MACC analysis are set out in Table 3.2 and Figure 3.2:. Details of the individual measures are given in chapter 4 of this document. The mean annual ammonia abatement potential under the S1 scenario between 2021 and 2030 was calculated to be 15.26 kt NH_3. However, it should be noted that mitigation potential reached circa 19 kilotonnes per annum in 2030 as some mitigation pathways are not fully implemented until 2030. Mitigation measures followed adoption pathways closely aligned with the Ag-Climatise strategy, where possible, meaning that uptake rate was not necessarily assumed to be linear as in Lanigan et al. (2015). Similar to the MACC in Lanigan et al. (2015) there were a few cost-beneficial measures identified. Six cost negative measures were i) lowering of crude protein content of bovine diets, ii) lowering of crude protein content of pig diets, iii) inclusion of clover, iv) use of protected urea, v) liming in grasslands and iv) covering of pig slurry stores. These cost negative measures indicated a potential cost saving of -€22.21 million, it should be noted that a number are predicated on efficiency gains driven by best management practice adoption with associated reductions in chemical N fertiliser application. The total cost of the seven measures that are cost positive was €33.07. Combining the cost positive and negative measures indicated a net total cost for implementing all measures of €10.86 million.

Two measures provided the bulk of available mitigation potential, with LESS for bovines delivering on average over 9 kt NH_3 per annum, and protected urea delivering a further average of over 3.1 kt NH_3 per annum. Therefore, these two measures combined can realise on average approximately 80% of the overall calculated mitigation potential. The results of the current analysis estimated ammonia abatement potential with full implementation of the mitigation pathways at 15.25 kt NH_3 compared to between 10.6 and 12.05 kt NH_3 mitigation potential in the previous MACC (Lanigan et al., 2015).

Table 3.1: Marginal Abatement Cost Curve Results

Pathway	**Average NH3 abatement (kt) per annum (2021-2030)**	**Average cost per annum (€'million) (2021-2030)**	**€ per kg NH_3 abated**
Crude Protein - Dairy	0.48	-€10.05	-€20.97
Clover	0.35	-€3.97	-€11.32
Crude Protein - Pigs	0.11	-€0.71	-€6.44
Protected Urea	3.11	-€7.15	-€2.30
Liming	0.31	-€0.33	-€1.06
Covered Stores - Pigs	0.19	-€0.002	-€0.01
LESS – Bovine	9.04	€12.64	€1.40
Covered Stores - Bovine	0.55	€0.80	€1.47
Amendments - Pig Slurry	0.18	€0.85	€4.68
LESS – Pigs	0.30	€1.71	€5.77
Amendments - Poultry	0.08	€0.97	€12.72
Amendments - Bovine	0.47	€13.03	€27.78
Poultry Manure - Drying	0.09	€3.07	€34.70
Total	**15.26**	**€10.86**	

Figure 3.2: Ammonia Marginal Abatement Cost Curve Chart for Activity Level Scenario S1

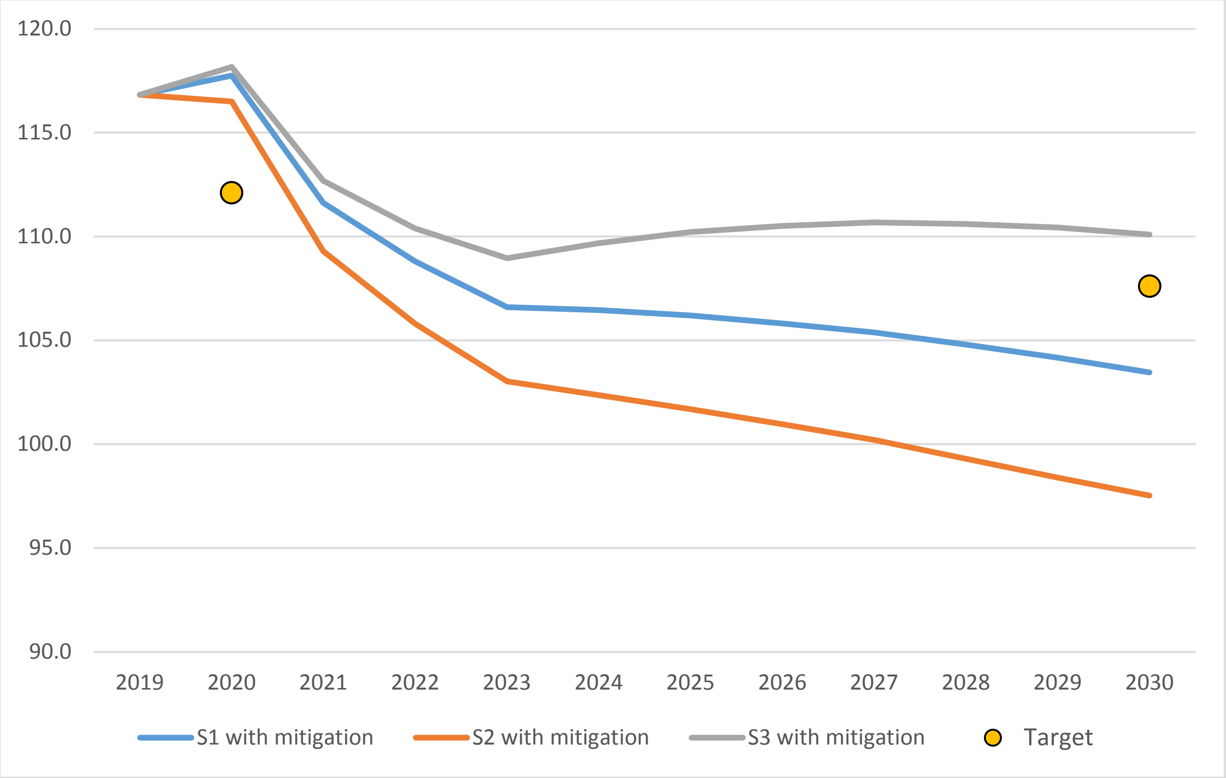


3.4 Implications of Mitigation for Compliance with Emissions

While Table 3.1 indicated total average abatement of the combined mitigation pathways to be circa 15.26 kilotonnes of NH_3 when related to the S1 activity levels, it should be noted that as some mitigation pathways are not fully implemented until 2030, it is not until the end of the period that maximum mitigation potential is reached. For S1 activity full mitigation potential of combined measures is estimated at 19 kilotonnes per annum by 2030. Figure 3.3 illustrates kilotonnes of NH_3 emitted under the S1, S2 and S3 scenarios under the assumption that full mitigation potential assumed in this analysis is realised by 2030. These projected levels of ammonia emissions are also compared with the maximum (target) level of emissions under the EU National Emission Ceiling Directive limits.

Results from this analysis indicate that full implementation of the mitigation pathways outlined here will allow Ireland to comply with the NECD (conditional on the assumed measure uptake) in the S1 and S2 scenarios. However, under S3 this cannot be achieved and additional measures will be required to meet obligations under this S3 scenario.

Figure 3.3: NH_3 Aggregate Levels with Full Mitigation Potential Realised (kilotonnes of NH_3)



3.5 Expected Future Developments in Ammonia Mitigation

MACC analysis is always time and context specific due to i) on-going and future scientific research that will lead to measures that cannot yet be evaluated; ii) future developments in agricultural and other policies that cannot currently be foreseen and iii) observed economic and agricultural activity which may change over time.

The research and analysis presented in this report, succeeds that presented in Lanigan et al. (2015), and in time more analysis will be necessary due to the availability of new economic and activity data, changes in policy and on-going and future research developments and developments in national emission inventory estimates.

Research developments that will require periodic assessment can be classified into four main categories as set out below:

1) National emission inventory refinement: The national emission inventory requires modification where new activities or emission factors become available and require incorporation into the national ammonia emission inventory. Based on on-going research and information from the inventory compilers changes that may occur in the short to medium term include revised national specific emission factors for trailing shoe, trailing shoe and injection, incorporation of manures to cropland, naturally ventilated housing, forced ventilation systems for animal housing, land-spreading of solid manures, outdoor lagoons and storage tanks and new fertiliser compounds. There is a need for country-specific emission factors from synthetic fertilisers (straight and compound forms containing N), as the current approach utilizes a combination of default values from the EMEP/EEA Emission Inventory Guidelines and country-specific mitigation potentials. As GHG and ammonia mitigation can be synergistic or antagonistic, country-specific data will assist with optimizing mitigation potential of both gaseous N losses. In addition, higher tiers of reporting (i.e. modelling of ammonia emissions) may be possible in the future that take account of the impact of abiotic factors such as weather and soil type.

2) Short-term research plans on mitigation technologies: This includes current on-going research, where findings will become available in the next five years. Considerable research is currently being undertaken: This research includes:
    a. The use of food processing waste streams (e.g. spent brewers grain, apple pulp, dairy production waste streams, etc.) as slurry amendments for housing/storage, as well as acidifiers (nitric acid, sulphuric acid, alum) during both the slurry storage and land-spreading phases.
    b. The use of injection techniques to land-spread slurry on grassland and the use of rapid incorporation techniques post spreading on cropland.
    c. The impact of slat mats and valves to reduce ammonia emissions from animal housing.

3) Medium-term research plans on mitigation technologies: This includes technologies that are in development, or have been researched elsewhere but require either Irish-

specific values or proof-of concept *in vivo* and could be available in 5 – 10 years. These include *inter alia*:
    a. The use of urease inhibitors and slow release compounds in housing and storage.
    b. The use of new urease inhibitors during land-spreading and on fertilisers.
    c. The use of a wider range of waste streams in outdoor storage.
    d. The use of covers to mitigate ammonia loss from farmyard manure (FYM).
    e. Rapid incorporation of FYM and poultry litter post land application.
    f. Reduction in crude protein levels in poultry diets.
    g. The use of ammonia scrubbers in forced ventilation systems in animal housing.
    h. The impact of topographical features such as windbreaks, row of trees etc., in preventing long-range ammonia transport.

4) Longer-term research plans on mitigation technologies: This includes technologies that require development and are only likely to become available over a longer time period > 10 years. These include:
    a. Low ammonia bovine housing with automated scraping systems and low surface area/volume slurry tanks.
    b. The development of cheap chemical sorbents to reduce ammonia in storage and forced ventilation animal housing systems.
    c. The development of technologies to mitigate NOx from manure management systems.

It should be noted that the majority of future emissions reductions will have to take place at the housing and storage levels, as the majority of mitigation associated with both the land-spreading of slurry and fertiliser will have already taken place, should the measures evaluated in this MACC analysis be fully implemented. The mitigation of emissions from FYM will become more important in the medium term, as even though activity is low in this category, ammonia emissions from it are relatively high. The rapid incorporation of bovine, pig and poultry manures on arable land may be a relatively low-cost strategy that would not only reduce ammonia, but also displace N fertiliser and build soil organic carbon stocks on low C soils. Housing/storage strategies, such as poultry litter drying and scrubber systems, as well as newly designed cattle housing, whilst effective, will be expensive and require either new buildings/storage tanks to be established or extensive retro-fitting works to be undertaken. Finally, critical load exceedance in terms of N deposition in vulnerable habitats is becoming a more pressing ecological problem. The development of landscape features, such as tree shelterbelts, designed to intercept plumes arising from point sources such as animal housing may become necessary. These features, if designed correctly, may also have co-benefits in terms of carbon sequestration and intercepting run-off of nutrients. However, to be effective thorough dispersion modelling and quantification of point source emissions will be required.

In terms of the wider sustainability of Irish agriculture, the requirement for a MACC analysis integrating mitigation measures across multiple environmental impacts such as gaseous emissions, water quality and biodiversity is more important than ever. This is particularly true in light of the newly announced EU Farm to Form and Biodiversity Strategies. Both strategies outline a number of far reaching recommendations and objectives for the future of the agricultural sector including, *inter alia,* a minimum 20% reduction in fertiliser use, a 50% reduction in nutrient losses and a 25% of agricultural land under organic farming by 2030. An integrated MACC analysis will guide the solutions that could help Irish agriculture to achieve these ambitious objectives across multiple environmental stressors, while taking into account the synergistic or antagonistic effects of individual mitigation measures across different environmental dimensions.

Finally, knowledge transfer (KT) has long been identified as vital in maximising the uptake of mitigation measures and achieving the identified mitigation potentials. Research by itself will not be able to lead to achievement of the mitigation potential without strong linkages to KT. Wide dissemination of research findings in a practical manner to Irish farmers combined with a demonstration of best practice by Teagasc and other farms will be necessary. Teagasc runs a number of KT initiatives that are focused on improving farm efficiency and hence reducing negative impacts on the environment. Examples of such initiatives are Carbon Navigator (in conjunction with Bord Bia), NMP Online, PastureBase Ireland and BETTER Farm programme. A new initiative “Signpost Farms” is currently being prepared for roll out. The Teagasc Signpost Farm programme will create a network of demonstration farms utilising a number of mitigation measures, and will showcase the best available practice to Irish farmers. Such initiatives demonstrating mitigation measures in an integrated and practical form are of utmost importance to enable understanding and uptake of the available technologies by Irish farmers. Furthermore, understanding barriers to uptake of mitigation measures and the role of KT in overcoming obstacles for adoption will be more important than ever.

4 Assumptions Employed and Effect of Mitigation Measures on S1 Activity Levels

For all the mitigation measures assessed in this section, the S1 scenario is used as the baseline for analysis .

4.1 Fertiliser Measures

4.1.1 Protected Urea

Description

This mitigation pathway involves the adoption of the Ag-Climatise proposal with substitution of all straight urea and 50% of CAN based fertilisers (mainly straight CAN & high CAN based compounds) for protected urea between 2021 and 2025. High CAN low PK compounds (e.g. N-P-K: 27-2.5-5, 24-2.5-10) are more amenable to replacement with protected urea from a practical soil fertility maintenance perspective.

Table 4.1: Results Protected Urea Fertiliser Mitigation Pathway

Abatement in 2030 (kilotonnes NH_3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
3.27	**-€9.25**	**3.11**	**-€7.15**	**-€2.30**

Rationale

Urea applied to agricultural land reacts with soil water and the enzyme urease, which hydrolyses urea-N to ammonium-N. During this hydrolysis process N losses occur through ammonia gas volatilisation to the atmosphere (Bouwman et al. 2002). Speed and magnitude of these reactions depend largely on soil and environmental factors such as temperature, moisture, wind speed, solar radiation and rainfall, with emissions under certain conditions as high as 50% of applied fertiliser N (Forrestal et al. 2016; Krol et al. 2020).These high ammonia losses from urea fertilisation can be reduced by implementing a change to protected urea, which is a form of urea with an added urease inhibitor such as N-(n-butyl)-thiophosphoric triamide (NBPT) (urea + NBPT) and / or N-(n-propyl)-thiophosphoric triamide (NPPT) (urea+ NBPT + NPPT). On average, ammonia gas emissions associated with urea application are 15.5% for straight urea (EEA/EMEP Guidebook, 2019), 3.3% for protected urea (Forrestal et al. 2016) and 0.8% for CAN (EEA/EMEP Guidebook, 2019), therefore the protected urea mitigation pathway offers approximately 78.5% reduction in NH_3 emissions for protected urea compared to straight urea fertiliser. Protected urea slows down N transformations in soil, thereby avoiding high concentrations of ammonium post fertiliser application which can cause ammonia gas emissions. Use of protected urea also aids plant uptake and fertiliser N recovery. The abatement associated with changing fertiliser N formulation results in less N loss from the soil and more N available for plant uptake.

Consequently, the volume of chemical N fertiliser inputs can be reduced, leading to additional mitigation.

Assumptions

Mitigation

All straight urea is replaced by protected urea. The transition will be stepwise between 2021 and 2023 (33% per annum) with full replacement in 2023 and for all years thereafter. In addition, a total of 50% of straight CAN is replaced by protected urea. The transition will be stepwise between 2021 and 2025 (10% per annum) with full 50% replacement in 2025 and all years thereafter. A total of 50% of high CAN low PK compounds (e.g. N-P-K: 27-2.5-5, 24-2.5-10) are replaced with protected urea. Analysis from the Teagasc National Farm Survey results in 2018 indicates that 69% of all N compounds applied by farmers fall into the high CAN low PK compound category. These compounds are amenable to substitution with protected urea, provided that soil fertility, in terms of P and K etc., is maintained with high PK compounds (e.g. N-P-K: 18-6-12 or 10-10-20 etc) and / or organic manure sources of P and K. In all 50% of the volume of high CAN low PK compounds are replaced stepwise between 2021 and 2025 (10% per annum) with full 50% replacement in 2025 and all years thereafter. It should be noted that the ammonia emission factors for straight CAN and CAN compounds are currently lower than that of protected urea, so this substitution has the effect of increasing emissions on the component of CAN based fertilisers substituted over the study period. The pathway specified here is in line with Ag-Climatise proposals and CAN replacement in this context is aimed at tackling greenhouse gas emissions from fertiliser N application. Greenhouse gas emissions, in the form of nitrous oxide (N_2O) gas, originating from CAN fertiliser applied to managed agricultural soils are higher than those from protected urea, hence from a GHG mitigation pathway perspective the substitution of 50% CAN with protected urea is also desirable (Lanigan et al., 2018). Reduction in ammonia emissions will improve NUE of the applied fertiliser as a result of the switch to protected urea. Quantity of fertiliser applied will be subsequently reduced to account for this efficiency gains.

Cost

The cost of the pathway is based on the quantities of straight CAN, high CAN low PK compounds, straight urea & protected urea fertiliser applied pre- and post-mitigation at market prices observed in 2020 (Wall, 2020a). The 2020 prices are used in each year of the scenario analysis to 2030. These are the only fertiliser categories that are projected to change in quantity relative to the baseline in the scenario analysis to 2030. All nitrogen use efficiency savings are assumed to be realised through the use of protected urea. Protected urea cannot be combined with phosphorus in an N-P-K compound, hence high CAN low PK compounds will need to be replaced with protected urea fertiliser for N and a separate P-K fertiliser for the phosphorus and potassium elements. Based on market prices in 2020 (Wall, 2020a), the price of P and K in compounds (with zero N) and straight formulations (P and K) is similar to the price of P and K components of high CAN low PK compounds being replaced. As farmers tend to apply fertilisers throughout the year in a number of splits (Wall, 2020a) it is assumed that farmers can, in the context of a nutrient management plan, implement the change from high CAN low PK compounds to a combination of protected urea and an alternative P-K fertiliser at no extra cost.

National emission inventory capture mechanism

Emissions associated with fertiliser use are accounted for by multiplying activity data (fertiliser use) by the appropriate emission factor. In the case of fertiliser activity, this is based on fertiliser volume sales per product type. Emission factors are specific to fertiliser types and are based on national and international research. The impact on ammonia emissions of this measure can be readily accounted for in the national emission inventory through the recorded sales of protected urea products and the application of the associated country-specific emission factor (Forrestal et al, 2016). As with all fertiliser products on the market, current levels of activity for protected urea are already being captured in relevant national statistics.

Barriers to uptake

This pathway involves a significant movement away from traditional fertiliser types (such as straight Urea & CAN) to protected urea. This technology and its widespread adoption will involve a significant shift in supply chain patterns by the agricultural fertiliser industry. For this measure to be fully adopted by farmers, as per our assumptions, it will need to be promoted by the fertiliser industry.

Concern has been expressed about potential residues from protected urea; research is currently on-going examining this concern.

Finally, protected urea has greater nitrogen use efficiency compared to straight urea; hence, the substitution will facilitate a reduction in chemical N application rates. Informing and convincing farmers to reduce application rates will require knowledge transfer initiatives and promotion.

Table 4.2*:* Overview of Modelling Assumptions Used and Results from Protected Urea Fertiliser Mitigation Pathway

Ag. Climatise - Protected Urea Pathway	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total Chemical N ('000 tonnes)	367.5	366.2	367.6	371.4	375.9	380.7	384.9	388.6	393.7	397.7	
Straight CAN ('000 Tonnes - Chemical N)	135.5	135.0	135.5	136.9	138.6	140.4	141.9	143.3	145.1	146.6	
NPK Compounds with CAN	178.7	178.1	178.7	180.6	182.8	185.1	187.2	189.0	191.4	193.4	
High CAN - Low PK Compounds ('000 Tonnes - Chemical N)	123.3	122.9	123.3	124.6	126.1	127.7	129.1	130.4	132.1	133.4	
High PK Compounds ('000 Tonnes - Chemical N)	55.4	55.2	55.4	56.0	56.7	57.4	58.0	58.6	59.3	59.9	
Straight Urea ('000 Tonnes - Chemical N)	47.6	47.4	47.6	48.1	48.7	49.3	49.8	50.3	51.0	51.5	
Protected Urea ('000 Tonnes - Chemical N)	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	
Other Fertilisers ('000 Tonnes - Chemical N)	4.0	3.9	4.0	4.0	4.1	4.1	4.2	4.2	4.2	4.3	
Assumptions - Mitigation Potential											
% Quantity Substitution - Protected Urea for Straight Urea	33%	66%	100%	100%	100%	100%	100%	100%	100%	100%	
% Quantity Substitution - Protected Urea for Straight CAN	10%	20%	30%	40%	50%	50%	50%	50%	50%	50%	
% Quantity Substitution - Protected Urea for high CAN - Low PK Compounds	10%	20%	30%	40%	50%	50%	50%	50%	50%	50%	
<u>Emission Factors (NH3 - g per kg)</u>											
CAN - Straight	8	8	8	8	8	8	8	8	8	8	
CAN Compounds	15	15	15	15	15	15	15	15	15	15	
Straight Urea	155	155	155	155	155	155	155	155	155	155	
Protected Urea	33	33	33	33	33	33	33	33	33	33	
<u>Fertiliser projections</u>											
Total Chemical N ('000 tonnes)	366.4	364.0	364.2	368.5	373.4	378.2	382.4	386.1	391.1	395.1	
CAN - Straight ('000 Tonnes - Chemical N)	121.9	108.0	94.9	82.2	69.3	70.2	71.0	71.6	72.6	73.3	
NPK Compounds	166.4	153.5	141.7	130.8	119.7	121.3	122.6	123.8	125.4	126.7	
CAN - Low PK Compounds ('000 Tonnes - Chemical N)	111.0	98.3	86.3	74.8	63.1	63.9	64.6	65.2	66.0	66.7	
High PK Compounds ('000 Tonnes - Chemical N)	55.4	55.2	55.4	56.0	56.7	57.4	58.0	58.6	59.3	59.9	
Straight Urea ('000 Tonnes - Chemical N)	31.4	15.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Protected Urea ('000 Tonnes - Chemical N)	42.3	82.9	123.7	151.6	180.4	182.7	184.7	186.5	188.9	190.8	
Other Fertilisers ('000 Tonnes - Chemical N)	4.0	3.9	4.0	4.0	4.1	4.1	4.2	4.2	4.2	4.3	
<u>Abatement Reduction / Increase (kilotonnes NH3)</u>											

Substitution Protected Urea for Straight Urea - NH3 Reduction	-2.0	-4.0	-5.9	-6.0	-6.1	-6.2	-6.2	-6.3	-6.4	-6.4	
Substitution Protected Urea for Straight CAN - Increase in NH3	0.4	0.7	1.1	1.4	1.8	1.8	1.8	1.9	1.9	1.9	
Substitution Protected Urea for Low PK Can Compounds – Increase in NH_3	0.2	0.5	0.7	0.9	1.2	1.2	1.2	1.2	1.2	1.3	
Total Net Reductions incl. NUE (kilotonnes NH3)	**-1.38**	**-2.81**	**-4.19**	**-3.65**	**-3.09**	**-3.13**	**-3.17**	**-3.20**	**-3.24**	**-3.27**	**-31.13**
Assumptions - Costs											
Chemical N savings ('000 tonnes) versus baseline	-1.11	-2.25	-3.36	-2.92	-2.48	-2.51	-2.54	-2.56	-2.60	-2.62	
€ per kg Straight CAN	€0.89	€0.89	€0.89	€0.89	€0.89	€0.89	€0.89	€0.89	€0.89	€0.89	
€ per kg in high CAN Compounds	€0.87	€0.87	€0.87	€0.87	€0.87	€0.87	€0.87	€0.87	€0.87	€0.87	
€ per kg straight urea	€0.72	€0.72	€0.72	€0.72	€0.72	€0.72	€0.72	€0.72	€0.72	€0.72	
€ per kg protected urea	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Cost (CAN, Urea, P. Urea) - Baseline Fertiliser (€'million)	€263.5	€262.6	€263.6	€266.3	€269.6	€273.0	€276.0	€278.7	€282.3	€285.2	
Cost (CAN, Urea, P. Urea) - Ag. Climatise Fertiliser Scenario (€'million)	€261.5	€259.2	€258.5	€259.4	€260.8	€264.2	€267.1	€269.7	€273.1	€276.0	
Total cost / benefit €'million (negative sign is a saving)	**-€2.05**	**-€3.41**	**-€5.13**	**-€6.91**	**-€8.74**	**-€8.85**	**-€8.95**	**-€9.04**	**-€9.15**	**-€9.25**	**-€71.49**
€ per kg NH3 abated (negative sign is a saving)	**-€1.49**	**-€1.21**	**-€1.22**	**-€1.89**	**-€2.83**	**-€2.83**	**-€2.83**	**-€2.83**	**-€2.83**	**-€2.83**	**-€2.30**

4.1.2 Liming

Description

Achieving the optimal soil pH through liming reduces the requirement for synthetic fertiliser; therefore this measure will reduce the required fertiliser volume and will interact with the measure (Protected Urea) which requires a change in the form of fertiliser nitrogen used.

Table 4.3: Results Liming Mitigation Pathway

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.56	**-€2.63**	**0.31**	**-€0.33**	**-€1.06**

Rationale

Soils in Ireland are naturally acidic and require applications of lime (usually as ground limestone ($CaCO_3$)) to neutralise this acidity and create a soil pH that is more favourable for crop growth, nutrient release and maintenance of soil quality. In naturally acidic soils, raising soil pH to an agronomic optimum level offers many benefits for crop production, soil nutrient availability and fertiliser efficiency.

Assumptions

Mitigation

The Farm Structures Survey 2016 (CSO, 2016) indicated that 4.09 million hectares in agriculture are under grass (excluding rough grazing). Currently, it is estimated that approximately 38% of the grassland area in Ireland is at a sub-optimal pH level (1.55 million hectares), this negatively impacts nutrient use efficiency (Plunkett & Wall, 2019), potentially leading to higher levels of fertiliser usage than would otherwise be necessary.

This pathway assumes that a total of 15% of the grassland area in Ireland (0.23 million hectares) is treated with lime on a stepwise basis from 2021 to 2030. This represents 40% of the grassland area with sub-optimal pH. It is assumed that this land is re-limed after four years to maintain benefits. It is also assumed that through achieving optimum pH through liming there is an increase in soil nitrogen supply through organic matter mineralisation processes of 70 kg N ha^{-1} yr^{-1} (Nyborg and Hoyt, 1978; Bailey, 1997; Culleton et al., 1999; Mkhonza et al., 2020), meaning that fertiliser nitrogen use can be reduced accordingly. Lime is assumed to be applied at the rate of 7.5 tonnes per hectare for the initial application and then at a rate of 5 tonnes per hectare maintenance rate for re-liming initial area (Fox et al., 2015). This would release over 16,000 tonnes of nitrogen by 2030; this volume of N released is assumed to be reflected in reductions in chemical N applications by farmers. The chemical N savings here are additive over the study period therefore the initial savings are modest compared to subsequent years and this is reflected in the cost of abatement at the start of the period. It should be noted that increased total liming costs are incurred in 2025 as the initial area is re-limed.

Cost

In the first instance, it is necessary to establish the pH of the soil. Hence, in line with recommended guidelines (Teagasc, 2020a) a soil sample is assumes to taken for every 3 hectares of land targeted under this pathway at a cost of €25 per sample to be tested in the laboratory (Teagasc, 2020b). It is assumed that initial land area limed is re-tested with a soil sample every 4 years. The cost of lime, including the cost of application to the field, is assumed to be €25 per tonne. In addition to the lime costs, this cost includes contractor charge for application based on prevailing market rates. It is assumed that this measure is applied in a manner consistent with the Ag-Climatise protected urea scenario and that all chemical N savings are captured through reduced protected urea fertiliser use at the same market prices (Wall, 2020a) used in evaluating the Protected Urea measure. It should be noted that liming has additional benefits not accounted for here such as additional phosphorus and potassium release from soils. This reduces the chemical fertiliser requirement for both these elements and represents a potential cost saving at farm level that has not been included here.

National emission inventory capture mechanism

This measure is not currently accounted for in the national emission inventory as a separately identifiable activity, as any savings in ammonia emissions are captured in reduced nitrogen fertiliser use, for a given level of agricultural activity. Therefore, the impact of this measure will be captured in the national emission inventory through activity data, i.e. via lower level of nitrogen fertiliser sales, relative to what would have been required had the measure not been implemented. It should be noted that from 2020 farms operating under a Nitrates Derogation must implement a 4-year liming programme as part of the Derogation conditions.

Barriers to adoption

Lime is often referred to as the forgotten fertiliser. The benefits from optimising soil pH are well established in terms of nitrogen availability from the soil as well as increased nitrogen use efficiency of chemical fertiliser applied. However, a significant portion of farmers habitually do not lime their land (Buckley et al., 2018) or test their soil to establish their land's pH levels. Derogation farms and farmers in the Green, Low-Carbon, Agri-Environment Scheme (GLAS) are required to soil test regularly (every 4 years) and to follow a farm nutrient management plan. The development by Teagasc of the Nutrient Management Planning (NMP) On-line system promotes this activity. However, a significant majority of farmers have not yet engaged in this NMP activity despite the demonstrated benefits of so doing. The continuing dominance of the con-acre model of short-term land leasing may be a significant impediment to adoption of this measure as farmers renting land on an annual lease hold basis may be less inclined towards optimal soil fertility (Lee, 1980).

Table 4.4*: Assumptions for Liming Mitigation Pathway*

Liming Pathway	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
UAA Grassland (million hectares)	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09	
UAA Grassland (million hectares) - sub optimal pH	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	1.55	
Total Chemical N (tonnes)	367,481	366,206	367,575	371,415	375,917	380,727	384,914	388,642	393,663	397,719	
Assumptions - Mitigation Potential											
% of Total UAA Grassland hectares - Newly Limed	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	
Lime applied - 1st time (million hectares)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	
Lime applied - 2nd time (million hectares)	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	
Lime applied - 3rd time (million hectares)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	
Cumulative area limed (million hectares)	0.02	0.05	0.07	0.09	0.12	0.14	0.16	0.19	0.21	0.23	
kg of N per hectare released from liming	70	70	70	70	70	70	70	70	70	70	
Quantity of Lime applied (tonnes per hectare) - Initial application	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	
Quantity of Lime applied (tonnes per hectare) - Maintenance	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	
Total lime applied (million tonnes)	0.17	0.17	0.17	0.17	0.29	0.29	0.29	0.29	0.41	0.41	
Total NH3 Reduction (kilotonnes)	**0.06**	**0.11**	**0.17**	**0.22**	**0.28**	**0.34**	**0.39**	**0.45**	**0.50**	**0.56**	**3.07**
Assumptions - Costs											
Number of soil samples (3 hectares average)	7,767	7,767	7,767	7,767	15,534	15,534	15,534	15,534	23,302	23,302	
Cost per soil sample	€25	€25	€25	€25	€25	€25	€25	€25	€25	€25	
Total soil sampling cost (€'million)	€0.19	€0.19	€0.19	€0.19	€0.39	€0.39	€0.39	€0.39	€0.58	€0.58	
Lime cost per tonne spread (€)	€25	€25	€25	€25	€25	€25	€25	€25	€25	€25	
Total Lime cost (€'million)	€4.4	€4.4	€4.4	€4.4	€7.3	€7.3	€7.3	€7.3	€10.2	€10.2	
Chemical N savings (tonnes) - Liming	1,631	3,262	4,893	6,524	8,156	9,787	11,418	13,049	14,680	16,311	
Chemical N savings (tonnes) - NUE	45	90	134	179	224	269	313	358	403	448	
€ per kg Protected Urea	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Cost saving fertiliser (€'million)	-€1.34	-€2.68	-€4.02	-€5.36	-€6.70	-€8.04	-€9.38	-€10.73	-€12.07	-€13.41	
Total cost (€'million) Liming Pathway	**€3.22**	**€1.88**	**€0.54**	**-€0.80**	**€0.97**	**-€0.37**	**-€1.71**	**-€3.06**	**-€1.29**	**-€2.63**	**-€3.25**
€ per kg NH3 abated (negative sign is a saving)	**€57.70**	**€16.85**	**€3.23**	**-€3.58**	**€3.46**	**-€1.12**	**-€4.39**	**-€6.84**	**-€2.57**	**-€4.71**	**-€1.06**

4.1.3 Clover

Description

Incorporating white clover into grassland swards can reduce to need for synthetic nitrogen fertiliser.

Table 4.5: Results Clover Mitigation Pathway

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.64	**-€10.28**	**0.35**	**-€3.97**	**-€11.32**

Rationale

White clover is a leguminous plant that can be incorporated into the grass sward to reduce the requirement for chemical N application, thereby avoiding the emissions from that volume of fertiliser that no longer needs to be applied. Once adequate clover proportion of > 20% is achieved in the sward, white clover is capable of natural nitrogen fixation (capturing nitrogen from the air and restoring it to the soil) of up to 80-200 kg N ha^{-1} yr^{-1} (Burchill et al., 2014; Phelan, 2012).

Assumptions

Mitigation

It is assumed that this measure is applied to 25% of specialist dairy farms as per the Teagasc National Farm Survey. These represent circa 4,000 dairy farms over this period, and have an average farm size of 58.1 hectares over the 2014 to 2018 period. It is assumed that 10% per annum of the area on these farms will be reseeded with clover over the 2021-2030 period and that this area will be over sown with clover every 5 years hence. It is also assumed that clover will replace 80 kg N ha^{-1} yr^{-1} of chemical N ha^{-1} yr^{-1} on these dairy farms.

Cost

Contractor rates of €116.14 per hectare are assumed for reseeding of grassland with clover (FCI, 2020). It is assumed that white clover is inserted during reseeding at the rate of 5 kg ha^{--1} at a cost of €10 per kg of seed (Humphreys, 2020). It is assumed that the initial reseeded area is over sown with clover 5 years after initial reseeding and that the farmer undertakes this process using his own broadcast fertiliser spreader. Hence, it's assumed the over sowing cost in terms of farmer's time is minimal and is based only on the cost of the clover seed sown (5 kg ha^{-1} at a cost of €10 per kg of seed). It is also assumed that this measure is applied in a manner consistent with the Ag-Climatise protected urea pathway and that all chemical N savings are capture through reduced protected urea fertiliser applications. It should be noted that chemical N fertiliser savings are additive over the study period (as the area sown with clover increases year on year), hence chemical N savings are modest in the initial years of the 2021-2030 period.

National emission inventory capture mechanism

This measure is not accounted for in the national emission inventory as a separate activity, as any savings in ammonia emissions come from reduced nitrogen fertiliser use activity.

Therefore, the impact of this measure will be captured in the national emission inventory through activity data, via lower nitrogen fertiliser sales, relative to what would have been required had the clover measure not been in place.

Barriers to adoption

There are a number of key steps for successful clover establishment and integration; (i) maintenance of optimum soil fertility (ii) high standards of grazing management, especially towards the end of grazing season i.e. frequent grazings, at reasonable grass covers (iii) requirement of proper post emergence spray management (use of clover safe sprays).

Incorporation and management of white clover at farm scale requires farmers to change their grassland management practices with substitution away from perennial ryegrass, chemical N fertilisers and standard chemical weed management. The benefits of clover are well established over a long period of time (Caradus et al., 1996; Burchill et al., 2014; Hennessy et al., 2020) yet adoption at farm scale has been low. Large scale uptake of this measure will require acceptance and buy in from various actors across the farming industry. White clover establishment and persistence will be reduced on farms where soil fertility is below optimum. Soils must be Index 3 for P and K and soil pH must be >6.3 for clover establishment and persistence. Hence, the incorporation of clover into grass swards requires a high level of management, in order to ensure optimal growth conditions. This requires that the farmer spends a larger amount of time ensuring that swards are over-sown, fertilised and tightly grazed at specific periods. Hence, there is a higher management and time cost associated with the use of higher clover swards, many farmers will require substantial advice and education in terms of sward management if clover is to be successfully established and retained in grass swards.

Table 4.6*:* Overview of Modelling Assumptions Used and Results for Clover Mitigation Pathway

Clover Scenario	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
25% of Dairy Farms in Teagasc NFS (number of farms represented)	4,008	4,008	4,008	4,008	4,008	4,008	4,008	4,008	4,008	4,008	
Average farm size (hectares)	58.1	58.1	58.1	58.1	58.1	58.1	58.1	58.1	58.1	58.1	
Assumptions - Mitigation Potential											
Dairy Land for clover insertion (hectares)	232,865	232,865	232,865	232,865	232,865	232,865	232,865	232,865	232,865	232,865	
% of area reseeded with clover	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	
% of area sown with clover	0%	0%	0%	0%	0%	10%	10%	10%	10%	10%	
% of total area converted to clover	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
Chemical N replacement rate (kg per hectare) with clover	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
Total hectares - Reseeded	23,286	23,286	23,286	23,286	23,286	23,286	23,286	23,286	23,286	23,286	
Total hectares - Oversown with clover	0.00	0.00	0.00	0.00	0.00	23,286	23,286	23,286	23,286	23,286	
Cumulative area sown with clover	23,286	46,573	69,859	93,146	116,432	139,719	163,005	186,292	209,578	232,865	
Total NH3 Reduction (kg)	**0.06**	**0.13**	**0.19**	**0.26**	**0.32**	**0.38**	**0.45**	**0.51**	**0.57**	**0.64**	**3.51**
Assumptions - Costs											
Cost per hectare of clover seed	€50	€50	€50	€50	€50	€50	€50	€50	€50	€50	
Cost per hectare of oversowing	€116	€116	€116	€116	€116	€116	€116	€116	€116	€116	
Cost of reseeding (€'million)	€3.9	€3.9	€3.9	€3.9	€3.9	€3.9	€3.9	€3.9	€3.9	€3.9	
Cost of oversowing (€'million)	€0.0	€0.0	€0.0	€0.0	€0.0	€1.2	€1.2	€1.2	€1.2	€1.2	
Chemical N savings (tonnes) - Clover	1,863	3,726	5,589	7,452	9,315	11,178	13,040	14,903	16,766	18,629	
Chemical N savings (tonnes) - NUE	51	102	153	205	256	307	358	409	460	511	
€ per kg Protected Urea	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Cost - Fertiliser (€'million)	-€1.53	-€3.06	-€4.59	-€6.12	-€7.66	-€9.19	-€10.72	-€12.25	-€13.78	-€15.31	
Total cost (€'million)	**€2.34**	**€0.81**	**-€0.72**	**-€2.26**	**-€3.79**	**-€4.15**	**-€5.69**	**-€7.22**	**-€8.75**	**-€10.28**	**-€39.71**
€ per kg NH3 abated	**€36.65**	**€6.32**	**-€3.79**	**-€8.84**	**-€11.88**	**-€10.85**	**-€12.73**	**-€14.14**	**-€15.24**	**-€16.12**	**-€11.32**

4.2 Bovine Measures

4.2.1 Low Emissions Slurry Spreading (LESS) Pathway - Bovine

Description

Movement away from using the splash plate method of slurry spreading to application by a low emission slurry spreading techniques for bovine slurry, such as a trailing hose or trailing shoe. This pathway follows that proposed in the Ag-Climatise report (DAFM, 2019).

Table 4.7: Results LESS Mitigation Pathway – Bovine Manures

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
11.69	**€16.33**	**9.04**	**€12.64**	**€1.40**

Rationale

Low emission slurry spreading techniques (LESS) are based on the principle of reducing the area of the ammonia emitting surface, in this case soil / plant surface that is covered by the applied liquid manure, and can reduce ammonia emissions by more than 50% when compared to emissions associated with the use of splash plate methods (Thorman et al. 2008). Low emission slurry spreading by **trailing hose** reduces the ammonia volatilising surface area by depositing slurry on top of grass in bands rather than broadcasting over a larger surface area. This results in 30% abatement in ammonia emissions from trailing hose in comparison to splash plate (Bittman et al., 2014). **Trailing shoe** application reduces the ammonia volatilising surface area by depositing slurry on the soil surface, underneath the grass. This results in 60% abatement in ammonia emissions from trailing shoe in comparison to splash plate (Bittman et al., 2014). Some studies suggested that LESS can lead to increased emissions of a potent greenhouse gas, nitrous oxide, however Irish studies on LESS applied to pasture and arable land (Meade et al. 2011; Bourdin et al. 2014) have not confirmed this. In the case of both LESS technologies, the measure preserves N fertiliser nutrient value in the deposited slurry. In consequence, this allows the volume of supplementation with synthetic nitrogen fertiliser application to be reduced by an offsetting amount equal to the nitrogen saved through use of the LESS technology, thereby avoiding ammonia emissions.

Assumptions

Mitigation

A recent report by Buckley et al., (2020) indicates a low level of bovine slurry application by LESS (4% in 2018). The ammonia inventories assumes 100% of slurry applied by splash plate in 2018 (Duffy et al., 2020) and this is assumed for the baseline here.

In line with Ag-Climatise (DAFM, 2019) a total of 60% of all bovine slurry spread that is applied is assumed to be spread by low emissions slurry spreading by 2022. This increases to 75% by 2025 and 90% by 2030. The measure is applied first to farms with a Nitrates Derogation followed by non-derogation farms. Derogation farms are estimated to account for 26% of the volume of slurry spread in Ireland (Teagasc National Farm Survey) and under the Nitrates Regulation these farms are obliged to apply all slurry by LESS from 2021. The proportion of slurry applied by LESS on non-derogation farms is assumed to increase stepwise to meet the Ag-Climatise objective of 90% by 2030. It is assumed that half of the slurry spread by LESS is applied by trailing shoe and half by trailing hose. The NH_3 abatement factor for trailing hose and trailing shoe application are 30% and 60% respectively based on Bittman et al. (2014).

Cost

Data from the Teagasc National Farm Survey indicates that 48% of aggregate slurry was applied by contractors in 2018. Contractor market rates for slurry spreading are employed as a proxy for the cost of slurry application. The Association of Farm & Forestry Contractors in Ireland (FCI) suggest a rate of €65 per hour for application of slurry by splash plate and €85 by trailing shoe method based on a 11,500 litre tanker. The number of tanker loads that are applied per hour depends on the distance between the tank and the spread lands. In this analysis it is assumed that 3 tankers of slurry per hour are applied using the splash plate (Burchill, 2019) method and 2.5 using the LESS methods, as the LESS method tends to be a little slower when applying slurry (Wall, 2020b). In this context, it is also assumed that spread lands are at distances away from the location where the slurry is stored that do not make the transport of slurry to these lands prohibitively expensive. These market rates for LESS slurry application are applied to the profile of slurry applied under the baseline S1 scenario versus the Ag-Climatise based LESS pathway to estimate the differential in overall aggregate slurry spreading costs. Additionally, LESS application leads to more N retention in slurry, which allows for a consequential reduction in the need for chemical N fertiliser use for a given level of agricultural production. Reduction in chemical N fertiliser is assumed to be realised in the form of reduced protected urea use that is costed at market rates per tonne of protected urea at 2020 (Wall, 2020a). The 2020 fertilisers prices are used in each year of the scenario analysis to 2030.

National emission inventory capture mechanism

Emissions associated with slurry land spreading are calculated by multiplying activity data and emission factors. Activity data in this case is the volume of manure produced by livestock (while housed) and the amount of nitrogen (as total N and ammoniacal N; TAN) in the manure spread in Ireland in spring, summer and autumn. Associated emission factors are derived from both Irish and international research. This measure can be incorporated into the national emission inventory as soon as activity data for the volume of slurry spread using LESS becomes available. These data are being collected by the Teagasc National Farm Survey (Buckley et al. 2020).

Barriers to adoption

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

Additionally, those farmers who feed hay (or round bale silage) with higher dry matter content to their livestock (predominantly farmers involved in beef production) may face practical difficulties in using LESS equipment for slurry application, due to the viscous nature of the slurry. Additional macerator may be required in such case, adding to the cost of the equipment

Table 4.8: Overview of Modelling Assumptions Used and Results for LESS Mitigation Pathway – Bovine Manures

LESS Pathway Bovine Slurry	**Year**										
Baseline Assumptions - S1 scenario	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Dry matter % - Dairy Slurry	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	
Dry matter % - Cattle Slurry	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	
Total slurry applied to land (million m3)	23.3	23.6	23.9	24.1	24.3	24.5	24.6	24.7	24.8	24.8	
Baseline - Proportion of slurry spread by LESS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
Baseline - Proportion of slurry spread by splash plate	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Quantity of bovine applied by LESS (million m3)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Quantity of bovine slurry by splash plate (million m3)	23.3	23.6	23.9	24.1	24.3	24.5	24.6	24.7	24.8	24.8	
m3 spread by LESS method per hour (11,500 litre tanker)	28.4	28.4	28.4	28.4	28.4	28.4	28.4	28.4	28.4	28.4	
m3 by splash plate method per hour (11,500 litre tanker)	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	
Market rate per hour for spreading using LESS (11,500 litre tanker)	€85	€85	€85	€85	€85	€85	€85	€85	€85	€85	
Market rate per hour for spreading using splashplate (11,500 litre tanker)	€65	€65	€65	€65	€65	€65	€65	€65	€65	€65	
Cost of LESS slurry spreading (€'million)	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	
Cost of splashplate slurry spreading (€'million)	€44.5	€45.1	€45.7	€46.2	€46.5	€46.8	€47.1	€47.2	€47.4	€47.4	
Total cost slurry spreading (€'million) - Baseline	€44.5	€45.1	€45.7	€46.2	€46.5	€46.8	€47.1	€47.2	€47.4	€47.4	
Mitigation Assumptions - LESS Pathway											
Total slurry stored (million m3)	23.3	23.6	23.9	24.1	24.3	24.5	24.6	24.7	24.8	24.8	
Proportion of Slurry on Derogation Farms	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	
Uptake Trailing Hose - Derogation Farms	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	
Uptake Trailing Shoe - Derogation Farms	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	
Proportion of Slurry on Non-Derogation Farms	74%	74%	74%	74%	74%	74%	74%	74%	74%	74%	
Uptake Trailing Hose - Non Derogation Farms	8%	16%	22%	28%	33%	35%	37%	39%	41%	43%	
Uptake Trailing Shoe - Non Derogation Farms	8%	16%	22%	28%	33%	35%	37%	39%	41%	43%	
Aggregate slurry applied by LESS	38%	50%	59%	67%	75%	78%	81%	84%	87%	90%	
Trailing hose % abatement factor	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	

Trailing shoe % abatement factor	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	
Total NH3 Emissions reductions including NUE (kiltonnes)	**5.10**	**6.12**	**6.78**	**8.23**	**9.66**	**10.09**	**10.51**	**10.91**	**11.31**	**11.69**	**90.40**
Cost Assumptions - LESS Pathway											
% of slurry applied using LESS	38%	50%	59%	67%	75%	78%	81%	84%	87%	90%	
% of slurry applied using splash plate	62%	50%	41%	33%	25%	22%	19%	16%	13%	10%	
Quantity of slurry applied by LESS (million m3)	8.8	11.8	14.1	16.2	18.2	19.1	19.9	20.7	21.5	22.2	
Quantity of slurry applied by splash plate (million m3)	14.4	11.8	9.8	8.0	6.1	5.4	4.7	4.0	3.3	2.6	
Cost of splashplate slurry spreading - LESS Pathway	€27.6	€22.6	€18.7	€15.2	€11.7	€10.4	€9.1	€7.7	€6.3	€4.9	
Cost of LESS slurry spreading ('million) - LESS Pathway	€26.5	€35.3	€42.2	€48.4	€54.5	€57.0	€59.5	€61.9	€64.3	€66.5	
Total cost slurry spreading - LESS Pathway	€54.1	€57.9	€60.9	€63.6	€66.3	€67.4	€68.6	€69.6	€70.6	€71.4	
Additional slurry spreading cost over baseline	€9.6	€12.8	€15.2	€17.5	€19.7	€20.6	€21.5	€22.4	€23.2	€24.0	
Chemical N Savings (tonnes) - LESS	-3,852	-5,115	-6,092	-6,971	-7,832	-8,170	-8,505	-8,827	-9,141	-9,446	
Chemical N Savings (tonnes) - NUE	-59	-68	-70	-96	-122	-133	-144	-155	-166	-176	
€ per kg N (Average of CAN & Urea)	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Fertiliser cost savings (€'million)	-€3.13	-€4.15	-€4.93	-€5.65	-€6.36	-€6.64	-€6.92	-€7.19	-€7.45	-€7.70	
Net cost of LESS Pathway	**€6.44**	**€8.61**	**€10.31**	**€11.83**	**€13.34**	**€13.96**	**€14.58**	**€15.18**	**€15.78**	**€16.33**	**€126.37**
€ per kg NH3 abated LESS Pathway	**€1.26**	**€1.41**	**€1.52**	**€1.44**	**€1.38**	**€1.38**	**€1.39**	**€1.39**	**€1.40**	**€1.40**	**€1.40**

4.2.2 Slurry Amendments - Bovine

Description

Use of amendments to lower ammonia emissions from slurry during storage.

Table 4.9: Results Slurry Amendments Mitigation Pathway – Bovine Manures

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.86	€23.76	0.47	€13.03	€27.78

Rationale

Typical amendments that have been widely researched and are commercially used in other European countries are chemical acidifiers, such as sulphuric acid and ferric chloride. A recent Irish study has shown that ferric chloride, sulphuric acid, aluminium sulphate ($Al_2(SO_4)_3 \cdot 14H_2O$) (commonly referred to as alum) and acetic acid are extremely effective in abating ammonia emissions during slurry storage by 96%, 85%, 82% and 73%, respectively (Kavanagh et al. 2019). Research is being carried out into alternative amendments to chemical acidifiers (waste products, microbial and physical amendments). Similarly, acidification in tanker during the land spreading phase has been reported to reduce emissions by between 42 and 95% (Kai et al. 2008; Stevens & Laughlin 1989; Seidel et al. 2017). Alum was assumed to be used under this mitigation pathway due to ease and safety of deployment (powder form versus specialist equipment for acids).

Assumptions

Mitigation

It is assumed that the compound alum is the amendment added to bovine slurry and that this reduces NH_3 at the slurry storage stage by 70%. It is also assumed that amendments are applied to an increasing proportion of slurry each year, increasing by 3 percentage points per annum from 2021 to 2030. Consequently, amendments will be applied to 30% of total bovine slurry in 2030. The effect of the use of the amendments is that more N is captured in slurry and returned to the soil at the land spreading stage of the manure management chain. This has the consequential effect of allowing for a reduction in chemical fertiliser requirements. This is assumed to be realised through reduction in rates of protected urea fertiliser applied.

Cost

It is assumed dairy bovine slurry has a dry matter content of 4% and cattle slurry has a dry matter content of 7%. Hence, the cost of treatment of dairy slurry is €2.34 per m^3 and for cattle slurry the cost is €4.40 per m^3 of slurry treated (Kavanagh et al., 2019). These prices are assumed to be held constant over the study period. Due to the addition of alum, more N is retained within the slurry. Hence, there is a reduced requirement for chemical N applications. The additional N retained over the baseline level represents a cost savings and is priced on the basis of the cost of protected urea fertiliser at market rates in 2020 (Wall, 2020a). As acid resistant concrete has been used in the construction of underground slurry storage tanks since the early 2000's no retrofitting of tanks is assumed to be necessary for implementation of this pathway.

National Inventory capture mechanism

The measure is currently not accounted for in the national emission inventory. As the scientific basis for the efficacy of these measures is well established, the measures can be incorporated into the national emission inventory as soon as activity data on the level of use of slurry amendments is available. Data on the use of these amendments by farmers is not currently collected by the Teagasc National Farm Survey but could be added to the Teagasc National Farm Survey survey data collection schedule or else captured using a mechanism similar to recording fertiliser sales.

Barriers to adoption

The slurry amendments have not been applied on Irish livestock farms to-date. If this pathway is to be pursued it will require significant knowledge transfer efforts to educate farmers as to what the benefits of amendments are as well as promotion by the industry. Farmer and industry acceptability of the use of amendments will also need to be considered. Potential for soil acidification as a result of the use of acidifying amendments also needs to be acknowledged and addressed, if required, by additional liming, cost of which would also need to be considered. Any potential regulations to the amount of alum land spread in the amended slurry are also need considering.

Table 4.10: Overview of Modelling Assumptions Used and Results for Slurry Amendments Mitigation Pathway – Bovine Manures

Bovine Slurry Amendment Pathway	**Year**										
Baseline Assumptions - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Dry Matter % - Dairy Slurry	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	
Dry Matter % - Cattle Slurry	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	
Total slurry stored (million m3)	23.36	23.66	23.94	24.18	24.38	24.52	24.64	24.72	24.77	24.78	
Total slurry stored (million m3) - Dairy	13.95	14.30	14.60	14.86	15.10	15.30	15.47	15.63	15.77	15.83	
Total slurry stored (million m3) - Cattle	9.40	9.36	9.34	9.31	9.28	9.22	9.16	9.09	9.00	8.95	
Mitigation Assumptions											
Alum efficacy rate co-efficient % reduction	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	
Adoption rate - % Slurry Treated	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	24.0%	27.0%	30.0%	
Total NH_3 Emissions reductions incl. NUE (kilotonnes)	**0.08**	**0.17**	**0.25**	**0.34**	**0.43**	**0.51**	**0.60**	**0.69**	**0.77**	**0.86**	**4.69**
Cost Assumptions											
Dairy Slurry Treated (m3)	0.42	0.86	1.31	1.78	2.26	2.75	3.25	3.75	4.26	4.75	
Alum - cost per m3 of dairy slurry @ 4.0% DM (€'million)	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	
Cattle Slurry Treated (m3)	0.28	0.56	0.84	1.12	1.39	1.66	1.92	2.18	2.43	2.69	
Alum - cost per m3 of cattle slurry @ 7% DM (€'million)	€4.40	€4.40	€4.40	€4.40	€4.40	€4.40	€4.40	€4.40	€4.40	€4.40	
€ per kg N (based on protected urea price)	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Chemical N Savings ('000 tonnes) - Amendments	0.07	0.13	0.20	0.27	0.34	0.41	0.48	0.55	0.62	0.69	
Chemical N Savings ('000 tonnes) - NUE	0.002	0.004	0.006	0.007	0.009	0.011	0.013	0.015	0.017	0.019	
Fertiliser cost (negative sign indicates saving) (€'million)	-€0.05	-€0.11	-€0.17	-€0.22	-€0.28	-€0.34	-€0.39	-€0.45	-€0.51	-€0.56	
Cost of slurry amendments (€'million)	€2.35	€4.74	€7.17	€9.63	€12.10	€14.57	€17.04	€19.50	€21.94	€24.36	
Total Cost (€'million)	**€2.29**	**€4.63**	**€7.00**	**€9.40**	**€11.82**	**€14.23**	**€16.65**	**€19.05**	**€21.43**	**€23.79**	**€130.30**
€ per kg NH_3 abated	**€27.80**	**€27.80**	**€27.79**	**€27.79**	**€27.78**	**€27.78**	**€27.78**	**€27.77**	**€27.77**	**€27.77**	**€27.78**

4.2.3 Covering of Slurry Stores

Description

Covering of slurry stores for all bovine manure generated.

Table 4.11: Results Covering of Slurry Stores Mitigation Pathway – Bovine Manures

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
1.01	**€0.61**	**0.55**	**€0.80**	**€1.47**

Rationale

Currently the majority of bovine slurry is stored in slatted tanks (67%) which are classified as 'covered', with the remainder stored in uncovered tanks, such as open over ground tanks (30%) (EPA, 2019). Fitting a slurry store with a cover significantly reduces ammonia emissions (Sommer et al. 2006). There are different types of covers, such as the natural crust formed on the slurry surface, straw, floating expanded clay balls and other floating materials, flexible covers and rigid roofs. The range of materials used as covers are associated with different levels of efficacy in their capacity to abate ammonia emissions. While tight lid covers exhibit ammonia reduction efficiency of approximately 80% compared to 60% for flexible covers and 40% for floating materials (Resi et al., 2015), there are also considerations around the applicability of different cover types to retrofitting existing and installing in new slurry tanks. Here, tight lid covers are the most expensive to fit, while flexible covers are lighter and therefore require less complicated engineering solutions, especially to retrofit. Hence, this analysis assumes the use of flexible floating covers over the whole surface of the slurry store.

Assumptions

Mitigation

This measure assumes that all currently uncovered slurry stores are covered by 2030, hence a 100% adoption rate is assumed, and this results in a reduction in the ammonia emission factor associated with slurry storage from the 10 % value used for uncovered stores to the 5% value used for covered stores (Misselbrook et al. 2016).It is assumed that there is a transition from 67% of slurry stored in covered stores (current inventory level) to 100% progressively over the period 2021 and 2030. This is to be achieved by an annual increase of 3.33 percentage points in the percentage of slurry stored under a covered system between 2021 and 2030.

Cost

Based on Reis et al. (2015) it is assumed that it costs €1.5 per m3 of slurry to substitute an uncovered slurry store for a covered slurry store based on installation of a flexible floating cover. Reduced losses at the slurry storage stage lead to an increased retention of N in the farm system. This is turn reduces the requirement for chemical N fertiliser for a given level of agricultural production. The additional N quantity retained can be then costed as a saving, in terms of reduced chemical N usage, based on market prices for protected urea fertiliser in 2020 (Wall, 2020a). The 2020 prices are used in each year of the scenario analysis to 2030.

National emission inventory capture mechanism

This measure is currently accounted for in the national emission inventory by using the percentage of covered vs uncovered stores observed in the facilities survey (Hyde et al., 2008) and the emission factors associated with both types of slurry stores. By recording activity data on the percentage of covered vs uncovered stores for future years, the associated ammonia mitigation will be reflected in the national emission inventory.

Barriers to adoption

This involves conversion from uncovered to covered bovine slurry stores. Depending on idiosyncrasies of individual farm layouts, adaption of existing structure may be logistically difficult in terms of implementation of a flexible floating slurry cover.

Table 4.12: Overview of Modelling Assumptions Used and Results for Covering of Slurry Stores Mitigation Pathway – Bovine Manures

Covering of bovine slurry stores pathway	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total Volume of Slurry Stored (million m3)	23.4	23.7	23.9	24.2	24.4	24.5	24.6	24.7	24.8	24.8	
% of Bovine slurry stores covered	66.9%	66.9%	66.9%	66.9%	66.9%	66.9%	66.9%	66.9%	66.9%	66.9%	
% of Bovine slurry stores uncovered	33.1%	33.1%	33.1%	33.1%	33.1%	33.1%	33.1%	33.1%	33.1%	33.1%	
% Dry slurry - Dairy Slurry	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	
% Dry Matter - Cattle Slurry	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	
Total volume of slurry - Covered Stores (million m3)	15.63	15.83	16.01	16.17	16.31	16.40	16.48	16.54	16.57	16.58	
Total volume of slurry - Uncovered Stores (million m3)	7.73	7.83	7.92	8.00	8.07	8.11	8.15	8.18	8.20	8.20	
Assumptions - Mitigation Potential											
% of Bovine slurry stores covered	70.2%	73.5%	76.8%	80.1%	83.4%	86.7%	90.0%	93.3%	96.6%	100.0%	
% of Bovine slurry stores uncovered	29.8%	26.5%	23.2%	19.9%	16.6%	13.3%	10.0%	6.7%	3.4%	0.0%	
Storage emission factor (proportion of TAN) covered store	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
Storage emission factor (proportion of TAN) uncovered store	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	
Total NH_3 Reduction incl. NUE (kilotonnes)	**0.09**	**0.19**	**0.29**	**0.39**	**0.49**	**0.60**	**0.70**	**0.80**	**0.90**	**1.01**	**5.45**
Assumptions - Costs											
Total volume of slurry - Covered Stores (million m3)	16.4	17.4	18.4	19.4	20.3	21.3	22.2	23.1	23.9	24.8	
Total volume of slurry - Uncovered Stores (million m3)	7.0	6.3	5.6	4.8	4.0	3.3	2.5	1.7	0.8	0.0	
Additional volume of slurry covered (million m3)	0.8	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	
Cost per m3 to cover	€1.5	€1.5	€1.5	€1.5	€1.5	€1.5	€1.5	€1.5	€1.5	€1.5	
Total cost of covering slurry (€'million)	€1.16	€1.04	€1.08	€1.11	€1.15	€1.18	€1.20	€1.21	€1.22	€1.26	
Chemical N savings (‘000 tonnes) - Covering stores	0.08	0.16	0.24	0.32	0.40	0.48	0.57	0.65	0.73	0.81	
Chemical N savings (‘000 tonnes) - NUE	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
Fertiliser Replacement price (€/Kg N - based on protected urea)	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Cost savings chemical N fertiliser (€'million)	-€0.06	-€0.13	-€0.19	-€0.26	-€0.32	-€0.39	-€0.46	-€0.52	-€0.59	-€0.65	
Total cost of covering bovine slurry stores (€'million)	**€1.09**	**€0.91**	**€0.88**	**€0.86**	**€0.82**	**€0.79**	**€0.74**	**€0.69**	**€0.64**	**€0.61**	**€8.03**
€ per kg NH_3 abated	**€13.15**	**€5.53**	**€3.73**	**€2.85**	**€2.33**	**€1.98**	**€1.71**	**€1.51**	**€1.35**	**€1.26**	**€1.47**

4.2.4 Reduction in Crude Protein in Diet– Dairy cows

Description

Reduction of animal N intake in dairy cows through a reduction in crude protein in concentrate feed.

Table 4.13: Results Crude Protein Mitigation Pathway – Dairy Cows

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.49	**-€10.30**	**0.48**	**-€10.05**	**-€20.97**

Rationale

Typically, livestock use less than 30% of N in their feed, with 50% to 80% of the remainder excreted in urine and 20% to 50% in dung. Urea is the major form of N in urine accounting for 97% of N in urine (McCrory and Hobbs, 2001). The concentration and form of N in cattle slurry varies according to diet, animal species and age (McCrory and Hobbs, 2001). As a result, crude protein levels influence both the total amount of N excreted and the proportion of N in urine and faeces. Through the reduction in the initial animal N intake, due to the lowering of the crude protein content of feed, this measure reduces the amount of N excreted by the animal and by extension reduces the volume of N entering the manure management chain. Since this measure is applied at the very beginning of the manure management chain, it has an impact on reducing N at all subsequent steps of the N flow cascade. The level of crude protein reduction will depend on the feed composition on dairy farms, historically farmers have tended to supplement with unnecessarily high crude protein concentrates which cows are grazing pasture. There is a limit to crude protein reduction in the dairy cow diet without affecting milk yield.

Assumptions

Mitigation

Based on research by Shalloo et al (2018) and O'Brien (2018), 17% of the total dairy cow diet is assumed to be derived from concentrates and the average crude protein percentage of these concentrates is set at 17%. Results from the Teagasc National Farm Survey indicated that, between 2014 and 2018, the average dairy cow was fed 1,045 kg of concentrates. This is assumed to hold for the study period to 2030. At this concentrate intake rate a 1 percentage point reduction in the crude protein content of dairy concentrates is associated with a 1.5 kg reduction in the N excretion rate of dairy cows (O'Brien & Shalloo, 2019). This approach is adopted in this instance. A 1 percentage point reduction in the crude protein of dairy cow concentrate feed is assumed without any influence on output. The lower crude protein level in feed is assumed to take effect from 2021 and is applied in all subsequent years to 2030.

Cost

As recommended by Patton (2020), it was assumed that a 1 percentage point reduction in crude protein (CP) in a blended concentrate ration would be generated by substituting a lower protein ingredient (e.g. distillers grains at 25% crude protein) for soybean (48% crude protein) at a rate of ±50kg/tonne in the concentrate feed's formulation. The proportion of all other ingredients is unchanged; therefore feed energy, mineral and micro nutrient contents remain similar.

A 1 percentage point crude protein reduction results in a €6 per tonne reduction in the price of dairy concentrates, based on the market price differential between the two protein ingredients in 2020 (Patton, 2020). This is applied to 1,045 kg of concentrates intake per cow.

National emission inventory capture mechanism

Animal diet is currently accounted for in the national emission inventory through a nitrogen excretion model which is related to feed intake calculations used to estimate methane emissions from the national herd. Once the excretion rate per animal type is established, the amount of total nitrogen in the process is calculated by multiplying the animal nitrogen excretion value for each animal category by the number of animals nationally in that category. This nitrogen then follows all the steps of nitrogen flow through the manure management chain. When the crude protein content of the animal diet is reduced, the initial amount of nitrogen entering the manure management chain decreases, and therefore has a beneficial impact in all subsequent steps of manure management-from housing, through to storage and land-spreading of the resultant manure. This measure can be readily captured in the inventory, when data on any reductions in the percentage crude protein in animal diet are provided.

Barriers to adoption

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

A concerted effort is required by knowledge transfer agents and the wider industry to persuade farmers of the need to reduce crude protein in dairy cow concentrates. Given the cost benefit to farmers, the lack of any adverse effect on herd performance and simplicity to implement, this measure can achieve widespread adoption in a relatively short timeframe (>50% herds in <24 months). However, a number of steps are needed to deliver this change. Initially, a collaborative campaign to better inform farmers and the wider industry on the practical fundamentals of protein and energy requirements in ruminants is required. Also, more regular inclusion of pasture/silage feed quality information (energy, protein, fibre) in routine KT activities would highlight the nutritional value and balance of high quality pasture at different times during the grazing season. Furthermore, the traditional use of crude protein as ‘shorthand’ for concentrate quality needs to be phased out with the cooperation of the feed manufacturing industry. Its current use may be explained in part by the mandatory declaration of proximate analysis of crude protein on feed labels; there is no corresponding standard for energy declaration. Nonetheless, shifting the perception of supplement quality to total nutrient content, its complementarity with grass, and cost benefit of reducing protein, would help to normalise the use of lower crude protein rations at grass.

Table 4.14: Overview of Modelling Assumptions Used and Results for Crude Protein Mitigation Pathway – Dairy Cows

Reduced Crude Protein in Dairy Cow Diet	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
No. of Dairy Cows (million head)	1.52	1.55	1.57	1.59	1.60	1.62	1.62	1.63	1.63	1.64	
Total Chemical N ('000 tonnes)	367.5	366.2	367.6	371.4	375.9	380.7	384.9	388.6	393.7	397.7	
% of Dairy Cow Diet fed as concentrates	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	
Crude protein % of dairy cow concentrates (DM basis)	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	17.0%	
Dairy Cow N excretion rate (per head)	105.6	106.4	107.2	107.9	108.7	109.5	110.3	111.1	111.9	112.8	
Assumptions - Mitigation Potential											
Crude protein reduction in Dairy Concentrates (DM basis)	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	
kg reduction in N excretion per 1% point CP reduction	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	
Adjusted Dairy Cow - N excretion rate	104.1	104.9	105.7	106.4	107.2	108.0	108.8	109.6	110.4	111.3	
Total NH_3 Reduction including NUE (kilotonnes)	**0.46**	**0.46**	**0.47**	**0.48**	**0.48**	**0.49**	**0.49**	**0.49**	**0.49**	**0.49**	**4.79**
Assumptions - Costs											
Concentrates fed per cow (kg per head)	1,049	1,049	1,049	1,049	1,049	1,049	1,049	1,049	1,049	1,049	
Price decline per tonne of concentrates 1% CP	€6	€6	€6	€6	€6	€6	€6	€6	€6	€6	
Cost reduction (€'million)	**-€9.57**	**-€9.75**	**-€9.89**	**-€10.01**	**-€10.10**	**-€10.17**	**-€10.22**	**-€10.26**	**-€10.28**	**-€10.30**	**-€100.53**
€ per kg NH_3 abated	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**	**-€20.97**

4.3 Pig Measures

4.3.1 Reduction of Crude Protein in Pig Diets

Description

Reduction of animal N intake in growing pigs above 20kg liveweight through a reduction in crude protein in concentrate feeds.

Table 4.15: Results for Crude Protein Mitigation Pathway - Pigs

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.11	-€0.73	0.11	-€0.71	-€6.44

Rationale

Dietary crude protein levels influence both the total amount of N excreted and the proportion of N in urine and faeces. This measure reduces the amount of N excreted by the animal and then entering the manure management chain through the reduction in the initial animal N intake. A meta-analysis carried out by Hou et al. (2015) confirmed a linear relationship between reduction of crude protein (CP) in the animal diet and amount of total N excreted. A 1 percentage point reduction in CP leads in this instance leads to a 1.4% reduction in N excretion rate (Hyde, 2020). Since this measure is applied at the very beginning of the manure management chain, it has an impact on reducing N at all subsequent steps of the N flow cascade.

Assumptions

Mitigation

It is assumed that crude protein reduction is possible in feeds for the grow-finisher pig category and this this reduction it feasible without impact on animal performance or output. In the national emission inventory, this relates to the "pig over 20 kg" category. This over 20 kg category is assumed to cover the weaner, finisher stage 1 and finisher stage 2 feeding levels. Currently the crude protein levels of the weaner, finisher stage 1 and stage 2 feed is assumed to be 20%, 18.7% and 18% and the dry matter intake is assumed to be 42.8, 69 and 92.6 kg per pig respectively (Hyde, 2020). From this baseline it is assumed that the crude protein in the weaner, finisher stage 1 and stage 2 feed could be reduced by 1%, 2% and 2% respectively without adverse effects on output in 2021 and in all subsequent years (Lawlor, 2020).

Cost

On a dry matter basis it is estimated that a 1%, 2% and 2% crude reduction in the weaner, finisher stage 1 and 2 diets would lead to a per tonne cost reduction of €3.66, €8.95 and €7.56 respectively on a dry matter basis (Lawlor, 2020). Dry matter intake is assumed to be held constant.

National emission inventory capture mechanism

Animal diet is currently accounted for in the national emission inventory through the nitrogen excretion model. Once excretion rate per animal type is established, the amount of total nitrogen is calculated by multiplying individual animal nitrogen excretion by the number of animals. When reducing crude protein content of the animal diet, the initial amount of nitrogen entering the manure management chain reduces, and therefore has a positive impact on all subsequent steps of manure management-from housing, through to storage and land-spreading of the resultant manure. This measure can be readily captured in the inventory, when data on any reductions in the percentage crude protein in animal diet becomes available.

Barriers to adoption

The increased use of co- products and/or by- products could increase the protein levels in pig diets. There are a number of co-products that are becoming more available to pig producers (mostly from the distillery and bakery sectors).

The lack of adoption of phase feeding on Irish farms during the grower/ finisher period is also limiting the capability to reduce crude protein in Irish grower pig diets.

The availability and price of synthetic amino acids such as valine, iso-leucine and leucine could also be a major barrier to the adoption of reducing the crude protein in Irish pig diets.

In an era of low protein diets which are heavily formulated to the 5th and even 6th limiting amino acid, it is important to be aware that deficiencies in some non- essential amino acids (NEAA) can arise and negatively affect pig growth. The most practical approach to avoid this outcome is to maintain a minimum (total) lysine to crude protein ratio in the diet of between 7.1 and 7.4 % (Goodband et al., 2014). Likewise, Millet et al. (2018) suggested that the Standardized Ileal Digestible (SID) lysine to crude protein ratio should not exceed 6.4 % so that protein is not limiting growth in piglets between 4 and 9 weeks of age.

A strong KT campaign needs to be developed to address and signpost this promotion of lower crude protein levels in Irish pig diets.

Table 4.16: Overview of Modelling Assumptions Used and Results for Crude Protein Mitigation Pathway – Pigs

Crude Protein Reduction in diet of Pigs over 20 kg	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Number of Pigs 20 Kg + ('million head)	0.95	0.95	0.96	0.96	0.97	0.98	0.98	0.99	0.99	1.00	
Pigs 20 Kg + N excretion rate (kg N per annum)	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20	
Weaner - Dry matter Intake (kg per head)	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	42.8	
Crude Protein % of weaner diet	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
Finisher stage one - Dry matter Intake (kg per head)	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	
Crude Protein % of finisher stage 1 diet	18.7%	18.7%	18.7%	18.7%	18.7%	18.7%	18.7%	18.7%	18.7%	18.7%	
Finisher stage two - Dry matter Intake (kg per head)	92.6	92.6	92.6	92.6	92.6	92.6	92.6	92.6	92.6	92.6	
Crude Protein % of finisher stage 2 diet	18.0%	18.0%	18.0%	18.0%	18.0%	18.0%	18.0%	18.0%	18.0%	18.0%	
Assumptions - Mitigation Potential											
% reduction in N excretion per 1% crude protein reduction	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	
Reduction in Crude Protein % of weaner diet	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	
Reduction in Crude Protein % of finishers stage 1	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	
Reduction in Crude Protein % of finishers stage 2	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	
Crude protein % reduction in feed of Pigs over 20 Kg - Weighted Average	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	
N excretion rate Pigs 20 over Kg – Adjusted (kg N per annum)	8.97	8.97	8.97	8.97	8.97	8.97	8.97	8.97	8.97	8.97	
Total NH_3 Reduction - Crude Protein Reduction (kilotonnes)	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	**1.10**
Assumptions - Costs											
Price decline per tonne of feed per 1% CP reduction - Weaner	€3.66	€3.66	€3.66	€3.66	€3.66	€3.66	€3.66	€3.66	€3.66	€3.66	
Price decline per tonne of feed per 2% CP reduction - Finishers stage 1	€8.92	€8.92	€8.92	€8.92	€8.92	€8.92	€8.92	€8.92	€8.92	€8.92	
Price decline per tonne of feed per 2% CP reduction - Finishers stage 2	€7.56	€7.56	€7.56	€7.56	€7.56	€7.56	€7.56	€7.56	€7.56	€7.56	
Cost saving Weaner feed (€'million)	€0.15	€0.15	€0.15	€0.15	€0.15	€0.15	€0.15	€0.15	€0.16	€0.16	
Cost saving finishers stage 1 feed (€'million)	€0.50	€0.50	€0.50	€0.50	€0.51	€0.51	€0.51	€0.52	€0.52	€0.52	
Cost saving finishers stage 2 feed (€'million)	€0.04	€0.04	€0.04	€0.04	€0.05	€0.05	€0.05	€0.05	€0.05	€0.05	
Total Cost savings (€'million)	**-€0.69**	**-€0.69**	**-€0.69**	**-€0.70**	**-€0.70**	**-€0.71**	**-€0.71**	**-€0.72**	**-€0.72**	**-€0.73**	**-€7.06**
€ per kg NH_3 abated	**-€6.44**	**-€6.44**	**-€6.44**	**-€6.44**	**-€6.44**	**-€6.45**	**-€6.45**	**-€6.45**	**-€6.45**	**-€6.46**	**-€6.44**

4.3.2 Covering of Pig Slurry Stores

Description

Covering of all currently uncovered pig slurry tanks.

Table 4.17: Results Covering Slurry Stores Mitigation Pathway - Pigs

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.36	**-€0.10**	**0.19**	**-€0.002**	**-€0.013**

Rationale

Currently the majority of pig slurry is already stored in covered tanks (87%) due to the indoor nature of pig rearing. Covering all stores reduces air exchange and N loss. Fitting a slurry store with a cover significantly reduces ammonia emissions (Sommer et al. 2006). The range of materials used as covers are associated with different levels of efficacy in their capacity to abate ammonia emissions. This analysis assumes the use of rigid covers over the whole surface of the slurry store.

Assumptions

Mitigation

This measure assumes the gradual coverage of all pig slurry tanks moving from the current share of covered stores of 87% to 100% and a reduction in the associated ammonia emission factor from slurry storage of 52% for uncovered stores to 13% for covered stores.

Cost

A cost of €4 per m^3 was assumed for the installation cost of switching from uncovered to covered pig slurry stores by deployed rigid covers (Reis et al., 2015). Under this measure additional N is retained within the slurry, hence there is a reduced requirement for chemical N fertiliser. The chemical N fertiliser savings that are assumed to arise due to the covering of pig slurry measure are costed at the currently prevailing price for protected urea fertiliser in 2020, which is used in each year of the scenario analysis to 2030 (Wall, 2020a).

National emission inventory capture mechanism

This measure is currently accounted for in the national emission inventory by using the percentage of covered vs uncovered stores observed in the farm facilities survey (Hyde et al., 2008) and emission factors associated with both types of slurry stores. By recording activity data, i.e. data on the percentage of covered vs uncovered stores in future years, the associated ammonia mitigation will be reflected in the inventory.

Barriers to adoption

In addition to cost of the slurry covering, the existing farm layout may make the adaptation of existing pig slurry storage structures to being covered difficult to achieve.

Table 4.18: Overview of Modelling Assumptions Used and Results for Covering Slurry Stores Mitigation Pathway – Pigs

Covered Slurry Stores - Pigs	**Year**										
Baseline Projections - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total Slurry stored (million m3)	2.45	2.46	2.47	2.48	2.49	2.51	2.52	2.54	2.55	2.56	
% of covered pig slurry stores	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	
% of uncovered pig slurry stores	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	
Total slurry (m3) - Covered store	2.14	2.14	2.15	2.17	2.18	2.19	2.20	2.22	2.23	2.24	
Total slurry (m3) - Uncovered store	0.31	0.31	0.31	0.31	0.32	0.32	0.32	0.32	0.32	0.33	
Assumptions - Mitigation Potential											
% of covered pig slurry stores	88.6%	89.8%	91.1%	92.4%	93.7%	94.9%	96.2%	97.5%	98.7%	100.0%	
% of uncovered pig slurry stores	11.4%	10.2%	8.9%	7.6%	6.4%	5.1%	3.8%	2.5%	1.3%	0.0%	
Total slurry (m3) - Covered store	2.17	2.21	2.25	2.29	2.34	2.38	2.43	2.47	2.52	2.56	
Total slurry (m3) - Uncovered store	0.28	0.25	0.22	0.19	0.16	0.13	0.10	0.06	0.03	0.00	
Additional Slurry (million m3) covered per annum	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	
NH_3 slurry storage emission factor - covered stores	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	
NH_3 slurry storage emission factor - uncovered stores	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	
Total NH_3 Reduction incl. NUE (kilotonnes)	**0.03**	**0.07**	**0.10**	**0.14**	**0.17**	**0.21**	**0.25**	**0.28**	**0.32**	**0.36**	**1.93**
Assumptions - Costs											
Reduction in chemical N fertiliser (‘000 tonnes) - Covering stores	0.03	0.06	0.08	0.11	0.14	0.17	0.20	0.23	0.26	0.29	
Reduction in chemical N fertiliser (‘000 tonnes) - NUE	0.001	0.002	0.002	0.003	0.004	0.005	0.005	0.006	0.007	0.008	
Fertiliser price (Protected Urea € per kg)	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Cost savings chemical N fertiliser (€ 'million)	-€0.02	-€0.04	-€0.07	-€0.09	-€0.11	-€0.14	-€0.16	-€0.19	-€0.21	-€0.23	
Cost per m3 of conversion from uncovered to covered pig stores	€4.0	€4.0	€4.0	€4.0	€4.0	€4.0	€4.0	€4.0	€4.0	€4.0	
Cost for additional covered storage ('million)	€0.12	€0.12	€0.12	€0.12	€0.12	€0.12	€0.13	€0.13	€0.13	€0.13	
Total Net Cost of Measure (€ 'millions)	**€0.10**	**€0.08**	**€0.05**	**€0.03**	**€0.01**	**-€0.01**	**-€0.04**	**-€0.06**	**-€0.08**	**-€0.10**	**-€0.024**
€ per kg NH_3 abated (negative sign is a saving)	**€3.00**	**€1.13**	**€0.52**	**€0.22**	**€0.05**	**-€0.07**	**-€0.15**	**-€0.21**	**-€0.26**	**-€0.29**	**-€0.013**

4.3.3 Slurry Amendments - Pigs

Description

Use of amendments to lower ammonia emissions from slurry during storage.

Table 4.19: Results Slurry Amendments Mitigation Pathway - Pigs

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.34	€1.57	0.18	€0.85	€4.68

Rationale

This measure employs the use of amendments that reduce ammonia emissions during slurry storage and at land spreading. Typical amendments that have been widely researched, and which are commercially used in other European countries, are chemical acidifiers, such as sulphuric acid and ferric chloride. A recent Irish study has shown that ferric chloride, sulphuric acid, aluminium sulphate ($Al_2(SO_4)_3{\cdot}14H_2O$) (commonly referred to as alum) and acetic acid were extremely effective in abating ammonia emissions during slurry storage by 96%, 85%, 82% and 73%, respectively (Kavanagh et al. 2019) which is in agreement with another Irish study of Brennan et al. (2015). The use of amendments in pig houses is outside the scope of this analysis due to lack of activity data in relation to housing configuration.

Assumptions

Mitigation

Alum was assumed to be used under this mitigation pathway due to ease and safety of deployment (powder form versus specialist equipment for acids). As acid resistant concrete has been used in the construction of underground slurry storage tanks since the early 2000's no retrofitting of tanks is assumed to be necessary for implemeneation of this pathway.

Cost

It is assumed that the pig slurry is treated with alum at a cost of €2.34 per m^3 of slurry treated (Kavanagh et al., 2019). Due to the addition of amendments to pig slurry more N is retained within the system and hence there is a reduced requirement for chemical N applications on farms where pig slurry is applied. Chemical N savings are costed based on the price of protected urea fertiliser at market rates (Wall, 2020a). The 2020 prices are used in each year of the scenario analysis to 2030.

National emission inventory capture mechanism

This measure is currently not accounted for in the national emission inventory. As the scientific basis for the efficacy of this measure is well established, the measure can be incorporated into the national emission inventory as soon as activity data on the level of use of slurry amendments is available. This data could in the future be collected using the same data collection mechanism as that for chemical fertilisers' sales.

Barriers to adoption

The slurry amendments measure has not been applied on pig farms to-date. If this pathway is to be pursued it will require significant knowledge transfer efforts to educate farmers as to what the benefits of amendments are as well as promotion by the agro-chemical industry. Potential for soil acidification as a result of the use of acidifying amendments such as alum also needs to be acknowledged and addressed, if required, by additional liming, cost of which would also need to be considered. Any potential regulations to the amount of alum land spread in the amended slurry are also need considering.

Table 4.20: Overview of Modelling Assumptions Used and Results for Slurry Amendments Mitigation Pathway – Pigs

Pig Slurry Amendment Pathway	**Year**										
Baseline Assumptions - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Pig slurry stored (million m3) - Baseline	2.45	2.46	2.47	2.48	2.49	2.51	2.52	2.54	2.55	2.56	
Dry Matter %	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	
Mitigation Assumptions											
Pig slurry stored (m3)	2.45	2.46	2.47	2.48	2.49	2.51	2.52	2.54	2.55	2.56	
Dry Matter %	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	
Alum efficacy rate co-efficient % reduction	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	
Adoption rate - % Pig Slurry Treated	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	24.0%	27.0%	30.0%	
Total NH_3 Emissions reductions incl. NUE (kilotonnes)	**0.03**	**0.06**	**0.10**	**0.13**	**0.16**	**0.20**	**0.23**	**0.27**	**0.30**	**0.34**	**1.82**
Cost Assumptions											
Pig slurry - Treated (million m3)	0.07	0.15	0.22	0.30	0.37	0.45	0.53	0.61	0.69	0.77	
Alum - cost per m3 of pig slurry (€'million)	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	€2.64	
Cost of Alum slurry treatment (€'million)	€0.19	€0.39	€0.59	€0.79	€0.99	€1.19	€1.40	€1.61	€1.82	€2.03	
Chemical N Savings (‘000 tonnes) - Amendments	0.026	0.052	0.078	0.10	0.13	0.16	0.19	0.21	0.24	0.27	
Chemical N Savings (‘000 tonnes) - NUE	0.002	0.003	0.005	0.007	0.009	0.011	0.012	0.014	0.016	0.018	
€ per kg N (based on protected urea)	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	
Fertiliser cost saving (€'million)	-€0.02	-€0.04	-€0.07	-€0.09	-€0.11	-€0.13	-€0.16	-€0.18	-€0.21	-€0.23	
Cost of pig slurry amendments (€'million)	€0.2	€0.3	€0.5	€0.7	€0.9	€1.1	€1.2	€1.4	€1.6	€1.8	
Total Cost (€'million)	**€0.15**	**€0.30**	**€0.45**	**€0.61**	**€0.76**	**€0.92**	**€1.08**	**€1.25**	**€1.41**	**€1.57**	**€8.51**
€ per kg NH_3 abated	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**	**€4.68**

4.3.4 Low Emissions Slurry Spreading (LESS) – Pigs

Description

Movement away from using a splash plate method of slurry spreading to application by a low emission slurry spreading technique for pig slurry, such as a trailing hose or trailing shoe.

Table 4.21: Results LESS Mitigation Pathway - Pigs

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.38	**€2.18**	**0.30**	**€1.71**	**€5.77**

Rationale

Low emission slurry spreading techniques (LESS) by either trailing shoe or hose reduces the ammonia volatilising surface area by depositing slurry in bands rather than broadcasting over a larger surface area. In the case of both LESS technologies, the measure preserves N fertiliser value in the deposited slurry. In consequence, this allows the volume of supplementation with synthetic nitrogen fertiliser application to be reduced by the same amount of nitrogen saved in avoided ammonia emissions to reflect these savings.

Assumptions

Mitigation

In line with Ag-Climatise (DAFM, 2019) a total of 60% of all pig slurry spread is assumed to be applied using low emissions slurry spreading by 2022. This increases to 75% by 2025 and 90% by 2030. It is assumed that half of the slurry is applied by trailing shoe and half by trailing hose. The NH_3 abatement factor for trailing hose and trailing shoe are 30% and 60% respectively, based on Bittman et al. (2014).

Costs

The Association of Farm & Forestry Contractors in Ireland (FCI) suggest a rate of €65 per hour for application of slurry by splash plate and €85 by trailing shoe method, based on a 11,500 litre tanker. It is assumed that 3 tankers of slurry per hour are applied under the splash plate method (Burchill, 2019) and 2.5 under the LESS method, as the LESS method tends to be a little slower when applying slurry (Wall, 2020b). These market rates are applied to the profile of slurry that is spread under the counterfactual baseline S1 scenario (where the usage of LESS does not increase), and that is then compared to this pathway (where LESS usage increases) to estimate the differential in overall aggregate slurry spreading costs, when LESS is adopted. The LESS application method leads to more N retention from pig slurry, which leads to a consequential reduction in the requirement for chemical N fertiliser applications on farms where this slurry is applied. Chemical N fertiliser savings that are assumed to arise are costed using the volume of protected urea displaced at the current market price for protected urea in 2020 (Wall, 2020a). This price is used for scenario analysis to 2030.

National emission inventory capture mechanism

Emissions associated with slurry land spreading are calculated by multiplying activity data by the associated emission factors. The activity data is the volume of manure produced by livestock and the amount of nitrogen (as total N and ammoniacal N; TAN) in the manure spread in Ireland in spring, summer and autumn. Associated emission factors are derived from national and international research. This measure can be incorporated into the national emission inventory as soon as activity data for the volume of pig slurry spread using LESS becomes available.

Barriers to adoption

Under current regulations, pig slurry cannot be imported onto farms with a Nitrates Derogation. Hence, this pig slurry is likely to be spread on arable or non-derogation grassland farms. Non-derogation farmers who own a splash plate tanker have invested in this machine and may be reluctant/unable to modify their equipment to spread using a LESS method or may be unwilling to bear the cost of employing a contractor (with LESS equipment) to spread their slurry. This may be especially the case for farmers in low income categories.

There needs to be a KT campaign to show the benefits of Low Emission Slurry Spreading to farmers so as to ensure that they reduce their chemical nitrogen usage in accordance with the reduced need that arises from the use of LESS. This needs to be targeted at all users of animal slurries to ensure maximum benefits from this and other LESS mitigation measures.

Table 4.22: Overview of Modelling Assumptions Used and Results for LESS Mitigation Pathway – Pigs

LESS Pathway Pig Slurry	**Year**										
Baseline Assumptions - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total Pig Slurry applied to land (million m3) - Baseline	2.26	2.27	2.28	2.29	2.30	2.32	2.33	2.34	2.35	2.37	
Dry Matter %	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	
Baseline - Proportion of Slurry spread by LESS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
Baseline - Proportion of Slurry spread by splash plate	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Quantity of bovine slurry applied by LESS (m3)	0	0	0	0	0	0	0	0	0	0	
Quantity of bovine slurry applied by Splashplate (m3)	2.26	2.27	2.28	2.29	2.30	2.32	2.33	2.34	2.35	2.37	
m3 spread by LESS method per hour (10,000 litre tanker)	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	
m3 by Splashplate method per hour (10,000 litre tanker)	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	
Market rate per hour for spreading using LESS (10,000 litre tanker)	€85	€85	€85	€85	€85	€85	€85	€85	€85	€85	
Market rate per hour for spreading using splash plate (10,000 litre tanker)	€65	€65	€65	€65	€65	€65	€65	€65	€65	€65	
Cost of LESS slurry spreading (€'million)	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	€0.0	
Cost of splashplate slurry spreading (€'million)	€4.9	€4.9	€4.9	€5.0	€5.0	€5.0	€5.0	€5.1	€5.1	€5.1	
Total cost slurry spreading (€'million)	**€4.9**	**€4.9**	**€4.9**	**€5.0**	**€5.0**	**€5.0**	**€5.0**	**€5.1**	**€5.1**	**€5.1**	
Mitigation Assumptions											
Aggregate pig slurry applied by LESS	30%	60%	65%	70%	75%	78%	81%	84%	87%	90%	
Aggregate pig slurry applied by splash plate	70%	40%	35%	30%	25%	22%	19%	16%	13%	10%	
Trailing hose % abatement factor	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
Trailing shoe % abatement factor	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	
Total NH3 Emissions reductions incl. NUE (kilotonnes)	**0.12**	**0.24**	**0.26**	**0.28**	**0.31**	**0.32**	**0.33**	**0.35**	**0.36**	**0.38**	**2.96**
Cost Assumptions											
Quantity of bovine slurry applied by LESS (million m3)	0.68	1.36	1.48	1.60	1.73	1.81	1.89	1.97	2.05	2.13	
Quantity of bovine slurry applied by splash plate (million m3)	1.58	0.91	0.80	0.69	0.58	0.51	0.44	0.37	0.31	0.24	
m3 spread by LESS method per hour	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	25.7	
m3 by splash plate method per hour	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	
Market rate per hour for spreading using LESS	€85	€85	€85	€85	€85	€85	€85	€85	€85	€85	
Market rate per hour for spreading using splash plate	€65	€65	€65	€65	€65	€65	€65	€65	€65	€65	

Cost of LESS slurry spreading ('million)	€2.2	€4.5	€4.9	€5.3	€5.7	€6.0	€6.2	€6.5	€6.8	€7.0	
Cost of splashplate slurry spreading	€3.4	€2.0	€1.7	€1.5	€1.2	€1.1	€1.0	€0.8	€0.7	€0.5	
Total cost slurry spreading	€5.7	€6.5	€6.6	€6.8	€7.0	€7.1	€7.2	€7.3	€7.4	€7.5	
Additional slurry spreading cost over baseline	€0.8	€1.5	€1.7	€1.8	€2.0	€2.1	€2.1	€2.2	€2.3	€2.4	
Chemical N Savings (tonnes) - Greater use of LESS	96	193	210	228	245	257	268	279	291	302	
Chemical N Savings (tonnes) - NUE	3	5	6	6	7	7	7	8	8	8	
Fertiliser price (€ per kg N based on protected urea)	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	€0.80	
Fertiliser cost saving (€'million)	-€0.08	-€0.16	-€0.17	-€0.19	-€0.20	-€0.21	-€0.22	-€0.23	-€0.24	-€0.25	
Net Cost (€'million)	**€0.69**	**€1.39**	**€1.51**	**€1.64**	**€1.77**	**€1.85**	**€1.93**	**€2.01**	**€2.09**	**€2.18**	**€17.06**
€ per kg NH3 abated	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**	**€5.77**

4.4 Poultry Measures

4.4.1 Drying of Poultry Manure

Description

Drying poultry manure to reduce ammonia emissions during the storage phase.

Table 4.23: Results Drying of Poultry Manure Mitigation Pathway

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.163	**€5.66**	**0.09**	**€3.07**	**€34.7**

Rationale

Poultry birds excrete N in the form of uric acid, which is subsequently hydrolysed to ammonium and this form of N is then vulnerable to ammonia loss. Drying poultry manure decreases hydrolysis of uric acid to ammonium, thus reducing pH of the manure.

Assumptions

Mitigation

Drying treatment reduces NH_3 emissions by approximately 40% (Reis et al., 2015). It is assumed that this measure is applied to poultry manure generated by layers, broilers and turkeys. An average dry matter content of 30% is assumed for this manure. This drying mitigation pathway is assumed to be adopted gradually between 2021 and 2030, starting from a base level of adoption at 0% and reaching 100% by the end of this commitment period.

Cost

Based on estimates detailed in Reis et. al (2015) as set out by Penkhues (2015) an average cost of drying poultry manure was assumed to be €28 per 100 bird places.

National emission inventory capture mechanism

This measure is currently not accounted for in the national emission inventory due to lack of activity data. As the scientific basis for the efficacy of this measure is well established, the measure can be incorporated into the national emission inventory as soon as activity data on the level of use of drying of poultry manure is available. There is currently no vehicle for the collection of these data as poultry farms are currently not within the sampling frame of the Teagasc NFS.

Barriers to adoption

In addition to the cost, there is potentially significant logistical issues with setting up a ventilation / drying system in an existing poultry housing set-up. This may entail significantly structural and installation works to implement the system.

Table 4.24: Overview of Modelling Assumptions Used and Results for Drying of Poultry Manure Mitigation Pathway

Poultry Manure Amendment Pathway	**Year**										
Baseline Assumptions - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total manure (million tonnes) - Baseline	0.32	0.33	0.33	0.34	0.34	0.34	0.34	0.34	0.34	0.35	
Dry Matter %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
No. of Layers ('000 head)	4,099	4,160	4,210	4,252	4,280	4,300	4,317	4,335	4,350	4,367	
No. of Broilers ('000 head)	13,663	13,867	14,035	14,175	14,266	14,333	14,390	14,450	14,502	14,556	
No of Turkeys ('000 head)	1,570	1,594	1,613	1,629	1,640	1,647	1,654	1,661	1,667	1,673	
Mitigation Assumptions											
Efficacy rate	40%	40%	40%	40%	40%	40%	40%	40%	40%	40%	
Adoption rate - % manure treated	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
Total Manure Dried (million tonnes)	0.0325	0.0659	0.1000	0.1347	0.1695	0.2043	0.2393	0.2747	0.3101	0.3459	
Total NH_3 Emissions reductions incl. NUE (kilotonnes)	**0.015**	**0.031**	**0.047**	**0.064**	**0.080**	**0.096**	**0.113**	**0.130**	**0.146**	**0.163**	**0.89**
Cost Assumptions											
Cost per 100 birds	€28.00	€28.00	€28.00	€28.00	€28.00	€28.00	€28.00	€28.00	€28.00	€28.00	
Chemical N Savings (‘000 tonnes) - Drying	0.012	0.025	0.038	0.051	0.064	0.077	0.091	0.108	0.117	0.131	
Chemical N Savings (‘000 tonnes) - NUE	0.0003	0.0007	0.001	0.001	0.002	0.002	0.003	0.003	0.003	0.004	
Fertiliser Price (€ per kg N based on protected urea)	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	
Fertiliser cost saving (€'million)	-€0.01	-€0.02	-€0.03	-€0.04	-€0.05	-€0.06	-€0.07	-€0.09	-€0.10	-€0.11	
Cost of drying (€'million)	€0.5	€1.1	€1.7	€2.2	€2.8	€3.4	€4.0	€4.6	€5.2	€5.8	
Total Net Cost (€'million)	**€0.53**	**€1.08**	**€1.64**	**€2.20**	**€2.77**	**€3.34**	**€3.92**	**€4.49**	**€5.07**	**€5.66**	**€30.71**
€ per kg NH_3 abated	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**	**€34.70**

4.4.2 Amendments for Poultry Manure

Description

Use of amendments and acidifiers to lower ammonia emissions from poultry manure during storage.

Table 4.25: Results Poultry Manure Pathway Mitigation Pathway

Abatement in 2030 (kilotonnes NH3)	Cost in 2030 (€'million)	Average per annum abatement 2021-2030 (kilotonnes NH3)	Average per annum cost abatement 2021-2030 (€'million)	Average cost efficacy (€ per kg abated)
0.13	**€1.82**	**0.08**	**€0.97**	**€12.72**

Rationale

Application of aluminium sulphate ($Al_2(SO_4)_3{\cdot}14H_2O$), commonly referred to as alum, is known to reduce ammonia volatilisation from poultry manures.

Assumptions

Mitigation

The addition of alum to poultry manure is assumed to reduce ammonia emissions by approximately 30% (Moore et al., 2000). It is also assumed that amendments are applied to 3% of poultry manure per annum, with this percentage increasing annually over the study period 2021 to 2030. Consequently, amendments will be applied to 30% of poultry manure in 2030.

Cost

It is assumed that the poultry manure is treated with alum at a cost of €18.72 per m^3 of manure treated assuming 30% dry matter (Kavanagh et al., 2019). Due to the addition of amendments more N is retained within the system and hence there is a reduced requirement for chemical N on farms where the amended poultry litter is spread. Chemical N savings are costed based on chemical N applications that are assumed to be displaced and the price of protected urea fertiliser at current market rates in 2020 (Wall, 2020a). This price is used in scenario analysis to 2030.

National emission inventory capture mechanism

This measure is currently not accounted for in the national emission inventory due to lack of activity data. As the scientific basis for the efficacy of this measure is well established, the measure can be incorporated into the national emission inventory as soon as activity data on the level of use of poultry manure amendments and acidifiers is available. This data could in the future be collected using the same data collection mechanism as chemical fertiliser sales.

Barriers to adoption

The manure amendments measure has not been applied on Irish poultry farms to-date. If this pathway is to be pursued it will require significant knowledge transfer efforts to educate farmers on the benefits of this measure as well as promotion by the agro-chemical industry. Similarly to amendments used in pig and cattle slurry, here also a potential for soil acidification as a result of using alum needs to be acknowledged. Such an effect can be addressed, if required, by additional liming, cost of which would also need to be considered. Any potential regulations to the amount of alum land spread in the amended poultry manure also need considering.

Table 4.26: Overview of Modelling Assumptions Used and Results for Amendments to Poultry Manure Mitigation Pathway

Poultry Manure Amendment Pathway	Year										
Baseline Assumptions - S1	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total manure (million m3) - Baseline	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.34	0.34	0.35	
Dry Matter %	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%	
Mitigation Assumptions											
Alum efficacy rate co-efficient % reduction	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	
Adoption rate - % manure treated	3.0%	6.0%	9.0%	12.0%	15.0%	18.0%	21.0%	24.0%	27.0%	30.0%	
Total Manure Treated (million tonnes)	0.0094	0.0191	0.0290	0.0390	0.0492	0.0596	0.0703	0.0812	0.0923	0.1037	
Total NH_3 Emissions reductions incl. + NUE (kilotonnes)	**0.008**	**0.016**	**0.025**	**0.033**	**0.094**	**0.102**	**0.109**	**0.117**	**0.125**	**0.132**	**0.76**
Cost Assumptions – Poultry manure Amendment Pathway											
Cost of Alum treatment per tonne of manure	€18.42	€18.42	€18.42	€18.42	€18.42	€18.42	€18.42	€18.42	€18.42	€18.42	
Chemical N Savings (‘000 tonnes) - Amendments	0.01	0.013	0.020	0.027	0.075	0.081	0.088	0.094	0.110	0.110	
Chemical N Savings (‘000 tonnes) – NUE	0.0002	0.0004	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003	
Fertiliser Price (€ per kg N based on protected urea)	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	€0.8	
Fertiliser cost saving (€'million)	-€0.01	-€0.01	-€0.02	-€0.02	-€0.06	-€0.07	-€0.07	-€0.08	-€0.08	-€0.09	
Cost of amendments (€'million)	€0.2	€0.4	€0.5	€0.7	€0.9	€1.1	€1.3	€1.5	€1.7	€1.9	
Total Net Cost (€'million)	**€0.17**	**€0.34**	**€0.52**	**€0.70**	**€0.84**	**€1.03**	**€1.22**	**€1.42**	**€1.62**	**€1.82**	**€9.68**
€ per kg NH_3 abated	**€20.87**	**€20.87**	**€20.87**	**€20.88**	**€9.00**	**€10.16**	**€11.19**	**€12.13**	**€12.98**	**€13.77**	**€12.72**

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