Assessment of measures for ammonia mitigation in Irish agriculture using marginal abatement cost curve analysis.

Chathurangá Daulagala[a*], Cathal Buckley[b], Dominika J. Krol[c], Trevor Donnellan[b], Kevin Hanrahan[b], Bernard Hyde[c], Gary J. Lanigan[c], James Breen[a]

[a] UCD School of Agriculture and Food Science, Dublin, Ireland
[c]Teagasc, Crops, Environment and Land Use Programme, Johnstown Castle, Co. Wexford, Ireland
[b] Teagasc, Rural Economy and Development Programme, Mellows Campus, Athenry, Co. Galway, Ireland
[c] Environmental Protection Agency, Regional Inspectorate, The Glen, Monaghan Town, Co. Monaghan, Ireland
*Corresponding author: chathuranga.daulagala@ucd.ie(Chathurangá Daulagala)

Abstract

Agriculture accounts for over 99% of ammonia emissions across the Republic of Ireland. Additionally, the country has not met emissions targets as set down under the EU National Emissions Ceilings Directive. This research explores the cost-effectiveness of a suite of ammonia mitigation measures relevant to animal based agriculture that pre-dominated across the Republic of Ireland and under three economic activity scenarios (i.e. business as usual scenario, low activity and high activity levels, and three technology adoption rates (i.e. low, moderate and high) over the 2022 to 2030 period. Findings show the significant influence of assumptions about future agricultural activity and adoption rates on emissions projections, emphasising the importance of these uncertainties when assessing the ability to achieve ammonia emission reduction targets. From the 13 mitigation measures examined for bovine, pigs, poultry farms, the potential ammonia mitigation ranged from 0.03 (Reducing Crude protein in pigs diet – medium adoption) to 13.22 (Low Emissions Slurry Spreading, Bovine - high adoption) kilotonnes over the study period. The use of protected urea, clover establishment in intensive dairy farms, and reduction of crude protein in bovine and pig diets were found to be cost-negative in all three economic activity scenarios. Finally, medium and high technology adoption rates assumed in this study will allow the Republic of Ireland to abate a sufficient quantity of ammonia to comply with the EU NEC Directive limits under the business as usual and low economic activity scenarios. However, without highest technology adoption rates assumed in this study, meeting the EU NEC Directive ammonia target is unachievable across all economic activity scenarios.

Keywords: Marginal abatement cost curve, activity scenarios, technology adoption, ammonia emission, animal based agriculture

1.0 Introduction

The Republic of Ireland (henceforth called Ireland) and other European countries have committed to reducing emissions of ammonia (NH_3) under the European Union's National Emission Ceiling (NEC) Directive (2016/2284/EU) (EC, 2016). This Directive implements the Gothenburg Protocol targets (part of the Convention on Long-Range Transboundary Air Pollution; CLRTAP) for EU Member States. In 2020, the NEC Directive established new national emission reduction commitments for each EU Member State, according to which Ireland is obliged to reduce its NH_3 emissions by 1% between 2021 and 2030 and by 5% post-2030 on the 2005 emission level (EPA, 2022). Ireland has breached its previous EU NEC Directive limits in seven of the ten reporting years and after a new directive introduced breached again in 2021. Furthermore, in January 2023, the European Commission issued an infringement notice to Ireland for not meeting the NECD requirements (EPA, 2023).

Simultaneously, EU Member States must comply with the EU Habitats Directive (92/43/EEC) to preserve biodiversity and undertake measures to maintain or restore natural habitats and wild species. Recent reporting under the EU Habitats Directive highlighted declining conditions in sensitive Irish habitats (National Parks & Wildlife Service, 2019). Moreover, a recent integrated policy analysis from de Vries et al. (2021) concluded that a reduction in N inputs of 59% may be necessary for Ireland to protect its water, air and biodiversity. Similarly, a United Nations Economic Commission for Europe (UNECE) report confirmed that a reduction of 30-50% in NH_3 emissions is required in UNECE countries to avoid damage to ecosystems and health (UNECE, 2020).

In 2020, agricultural NH_3 emissions in Ireland rose to 123.4 kt, exceeding the 2005 level by 3.1%. Ireland's 2020 target, as per the NECD, was a 1% reduction from the 2005 baseline.

Animal manures produce about 90% of ammonia emissions, while chemical fertilisers account for the remainder (EPA, 2022). It is estimated that approximately 12.3 per cent of the nitrogen in animal manures and 2.6 per cent of nitrogen in chemical fertilisers is lost to the atmosphere as NH_3 on average (EPA, 2022).

Ammonia is an air pollutant and an indirect source of greenhouse gas (GHG) in the form of nitrous oxide (N_2O). In agriculture, NH_3 volatilisation represents a loss of nitrogen (N) from the system and has negative impacts on the environment through wet and dry deposition, causing acidification and eutrophication of natural ecosystems (Cameron et al., 2013). In the atmosphere, NH_3 plays a key role in the formation of fine particulate matter ($PM_{2.5}$), which is considered a major environmental risk to human health (Hristov, 2011; Stokstad, 2014).

As methodologies improved over the years due to more refined emission factors and access to more detailed activity data, the quantification of NH_3 emission inventories has improved. This has indicated that total quantities emitted have increased globally. Agriculture accounts for between 80 and 90% of total NH_3 emissions globally and the contribution from synthetic fertiliser has increased from circa 1.9 to 16.7 megatonnes NH_3-N yr^{-1} between 1961 and 2010 (Xu et al., 2019).

Agriculture is responsible for virtually all of Ireland's NH_3 emissions (99.4%; Hyde et al., 2022). Despite, the use of synthetic fertiliser decreasing by 16.4% between 1990 and 2020 (Hyde et al., 2022), emissions of NH_3 increased by 12.3%, driven by increased livestock populations and associated manure management practices.. Ammonia also remains the main loss pathway for reactive nitrogen (Nr) in agricultural systems (Burchill et al., 2016), where Nr is biologically, photochemically and radiatively active and can cause negative impacts via eutrophication and/or acidification of ecosystems and waterways.

Ammonia mitigation is a key challenge for agriculture, not only in Ireland but throughout the EU. In 2019, agriculture was responsible for between 81% (Portugal) and 99% (Ireland) of national NH_3 emissions within the EU-28 (Eurostat, 2021a). Simultaneously, Ireland reported the ninth highest national NH_3 emissions level in absolute terms despite its relatively small area and population size, highlighting the large agricultural emission base. However, Ireland is not the only EU Member State grappling with compliance with the NEC Directive. Out of 28 EU member states, 14 countries received formal notice from the European Commission in January 2023 noting non-compliance and calling to respect their emission reduction commitments as required by Directive 2016/2284 (EPA, 2023). Only nine EU member countries are projected to comply with the 2030 commitment period (EEA, 2019).

In the EU, the management of livestock manure is responsible for more than 70% of NH_3 emissions (UNECE, 2020), with notably 50% originating from bovines. In Ireland, this figure is even higher, standing at approximately 79% (Hyde et al., 2022). This elevated percentage can be attributed to the predominant practice of ruminant-based agricultural production. Consequently, taking action to mitigate NH3 emissions, particularly those associated with managing animal waste, becomes of paramount importance.

It is worth highlighting that extended grazing patterns associated with Irish agriculture contributes to lower emissions. Only 11% of NH_3 emissions in Ireland originate from grazing practices. The second most significant source of NH_3 emissions in the agricultural sector is linked to the use of synthetic fertilisers (Xu et al., 2019). In Ireland, synthetic fertilisers account for 9% of NH_3 emissions (Hyde, 2022), which is notably lower than the EU average of 17% (Eurostat, 2021b). The remaining emissions are associated with manure management during the housing, storage and land spreading phases.

Irish agriculture is dominated by a bovine pastoral-based system of production, with 92.8 % of the utilisable agricultural area comprised of permanent grassland (CSO, 2022). This, in turn, determines the NH_3 abatement practices available. Broadly, options to mitigate NH_3 in livestock-based agriculture focus on improvements in the management of animal manures and synthetic fertiliser use since these are the main emission sources. Abatement options vary in terms of their efficacy, cost, ease of implementation, acceptability, and requirements for verification (Reis et al., 2015).

Some of the better known management options to reduce NH_3 emissions in agricultural settings are animal feeding strategies (i.e. low protein feeds, increasing non-starch polysaccharide content of the feed), animal housing strategies (i.e. cleaning and scrubbing surfaces, removal of urine, separation of urine and faeces, manure cooling or drying), manure storage (i.e. decreasing surface area of manure storage, encouraging crusting, covering open stores, minimising disturbances such as aeration, lowering pH), low emission manure land spreading methods (i.e. band spreading, trailing shoe and injection, manure incorporation, spreading of diluted or acidified manure) and low emission fertiliser formulations (i.e. urease inhibitor added to Urea, commonly referred to as protected Urea) (Bittman et al., 2014; Reis et al., 2015).

Although many NH_3 emissions abatement management practices exist and are technically feasible, their applicability at farm system scale and acceptability vary significantly, and it is not readily clear which options can deliver mitigation in the most cost-effective manner. One way to identify preferred options is through the calculation of cost-effectiveness metrics using a marginal abatement cost curve (MACC) methodology. MACC is an approach that represents a) the level of abatement potential provided by mitigation measures and b) the costs associated with each of these measures. As such, it ranks the mitigation measures according to their respective cost per unit of mitigation delivered. In principle, this provides a ranking of which measures should be prioritised on the basis of cost, with the less expensive (or even profit-enhancing) mitigation measures preferred over more costly measures. A MACC also shows the potential volume of mitigation delivered for a given cost. The MACC methodology has previously been developed and applied to agricultural GHG mitigation (Smith et al., 2007; MacLeod et al., 2010; Ragnauth et al., 2015; Lanigan et. al., 2023). However, MACCs for agricultural NH_3 abatement are not yet common, with only a limited literature available and significant differences in the modelling approaches and tools used, i.e. N flow modelling using NARSES, MITERRA-EUROPE or simple calculation algorithms (Webb et al., 2005; Oenema et al., 2009; Zhang et al., 2020; Lenerts et al., 2021). Additionally, these published NH_3 MACC studies do not apply the MACC approach to projections of NH_3 over a multi-year period and assume static measure uptake.

This paper is novel as it examines the cost-effectiveness of NH3 mitigation measures in bovine-dominated agricultural systems and their overall effectiveness from 2022 to 2030 in achieving EU NEC Directive 2016/2284 compliance under three hypothetical technology adoption rates. The specific objectives of this paper are firstly, to assess how much ammonia per year can be abated under three economic activity scenarios and three technology adoption rates and secondly, to identify under what activity level and mitigation measure adoption rate can Ireland achieve NH3 limits under NEC Directive and finally, to identify agricultural policy options to achieve ammonia emission targets.

2.0 Materials & Methods

The following section outlines the data and modelling approach adopted as well as the mitigation measures chosen for investigation.

2.1 Data & Modelling Approach

Ammonia emissions projections are estimated based on emission factors applied to projections of future agricultural activity data. This analysis is conducted at a national aggregate level scale over the 2022 to 2030 temporal horizon, with 2022 as the base year.

2.1.1 Activity data

This analysis uses activity data, including animal and fertiliser use projections, sourced from the FAPRI-Ireland economic model of the Irish agricultural sector (Donnellan & Hanrahan, 2021). This model, established in 1997, employs econometric methods and utilizes annual time series data from the CSO and Eurostat. Operating over a 10-year horizon, the FAPRI-Ireland model forecasts various facets of the agricultural sector, encompassing activity levels, supply and demand balances for agricultural commodities, commodity and input prices, and economic accounts for agriculture (Donnellan and Hanrahan, 2006). It is closely linked to the FAPRI EU (GOLD) model (Hanrahan, 2001; Westhoff and Meyers, 2010) and shares similarities with models like the OECD AGLINK model, utilized by the OECD and the European Commission for their outlook publications (OECD, 2015; EC, 2021).

The FAPRI-Ireland model incorporates macroeconomic projections, including GDP growth rates, inflation, exchange rates, and population figures, from the ESRI COSMO model of the Irish macroeconomy (Bergin et al., 2016). It has been previously employed to analyse various agricultural policy and trade issues (Binfield et al., 2003; Binfield et al., 2004; Binfield et al., 2008; Donnellan et al., 2014) and has contributed projections to Ireland's Environmental Protection Agency (EPA) for reporting GHG emissions under the Monitoring Mechanism Regulation 525/2013 (EC, 2013).

This study employs three scenarios generated by the FAPRI-Ireland model: Business as usual (S1), Low (S2), and High (S3) activity level scenarios (Donnellan and Hanrahan, 2021). These scenarios were developed for sensitivity analysis in the context of reporting emissions under the Monitoring Mechanism Regulation and account for uncertainties in commodity markets and policies influencing future agricultural activity in Ireland through 2030.

The macroeconomic projections from the ESRI COSMO model and international agricultural commodity and input prices from the FAPRI-EU model remain consistent across these three scenarios. The primary driver of NH_3 emissions in Irish agriculture is the level of bovine activity. Variations among the scenarios primarily pertain to differences in dairy and beef cow numbers, associated cattle progeny, land use, fertilizer usage and other inputs. It is important to note that these projections are based on different assumptions about future policy and market conditions, serving to highlight the range of potential agricultural activity outcomes amid policy and market uncertainty. Appendix 1 shows the animal populations and chemical fertilizer usage for the year 2030 under the three scenarios.

Given the uncertainties surrounding future economic and policy variables, including agricultural output, input prices, subsidies, and trade tariffs, precise forecasts of future agricultural activities and NH_3 emissions from agriculture are unattainable. Table 1 summarizes the key assumptions underpinning the three activity-level scenarios used in this analysis.

Table 1: Summary of Scenarios Analysed

Scenario	Policy assumption
S1 (Business as usual)	No new bilateral trade agreements are entered into by either the EU or UK that offer other third countries preferential market access to EU and UK markets. The current level of support available under the EU Common Agricultural Policy (CAP) continues.
S2 (Lower activity level)	The growth rate in dairy cow inventories over the medium term is lower than under the Base case, while the rate of contraction in the beef cow herd that is projected is stronger than under the base case.
S3 (Higher activity level)	The growth in the dairy inventory is higher than under the Base Case and the contraction in the beef cow inventory is slower than under the Base Case.

2.1.2 Emissions Factors

The emissions factors applied to the activity level data (under S1 to S3) followed that of Hyde et al. (2022) in reporting Ireland's emissions to the secretariat of the UNECE convention on long-range transboundary air pollution and to the European Union under Directive (2016/2284/EU).

2.1.3 Modelling Approach

The modelling employed utilised the national NH_3 emission inventory developed by Ireland's Environmental Protection Agency in its reporting on national NH_3 emissions (Hyde et al., 2022). This approach generates emissions across a number of categories, including cattle, sheep, pigs, poultry, goats, horses/mules, chemical fertiliser and other minor emission sources. It also reports emissions generated at different stages of the production cycle (animal housing, manure storage, land spreading of manures, emissions while grazing, and emissions while in a collection yard (dairying). Appendix 1 shows the animal populations, fertiliser usage and other assumptions for each of the economic activity scenarios. Table 2 below summarises the combinations of economic activity levels and technology adoption rates assessed in this study. Table 2 shows the three technology adoption rates assumed under each of the activity scenarios. The adoption rate assumptions underpinning these scenarios are outlined in appendix 2.

Table 2 Scenarios modelled

Activity Level	**Business as usual (S1)**			**Low activity (S2)**			**High activity levels (S3)**		
Adoption Rates	Low	Medium	High	Low	Medium	High	Low	Medium	High
Scenario name	S1L	S1M	S1H	S2L	S2M	S2H	S3L	S3M	S3H

2.2 Technology Adoption

NH_3 abatement measures were selected based on an extensive review of international literature (Misselbrook et al., 2006; Reis et al., 2015; Bittman et al., 2014). Whenever possible, Irish-specific emission factors and cost data for these measures have been incorporated. In cases where Irish data was unavailable, the best available international data sources were used. Adoption rates for these measures were determined by considering the current adoption rate, as indicated by the Teagasc National Farm Survey data 2022[1] , Ag Climatise (2020) policy and with considerations of economic and biophysical constraints. Ag Climatise

---

[1] Teagasc National Farm Survey is operated as part of the EU Farm Accountancy Data Network. A random, nationally representative sample of farms is selected annually in conjunction with the Central Statistics Office (CSO).

(2020) policy has set targets for the use of low emission slurry spreading equipment, protected urea, liming and, covered slurry storage tanks. The high technology adoption rates assumed in this study for the above measures are stretch targets based on policy targets.

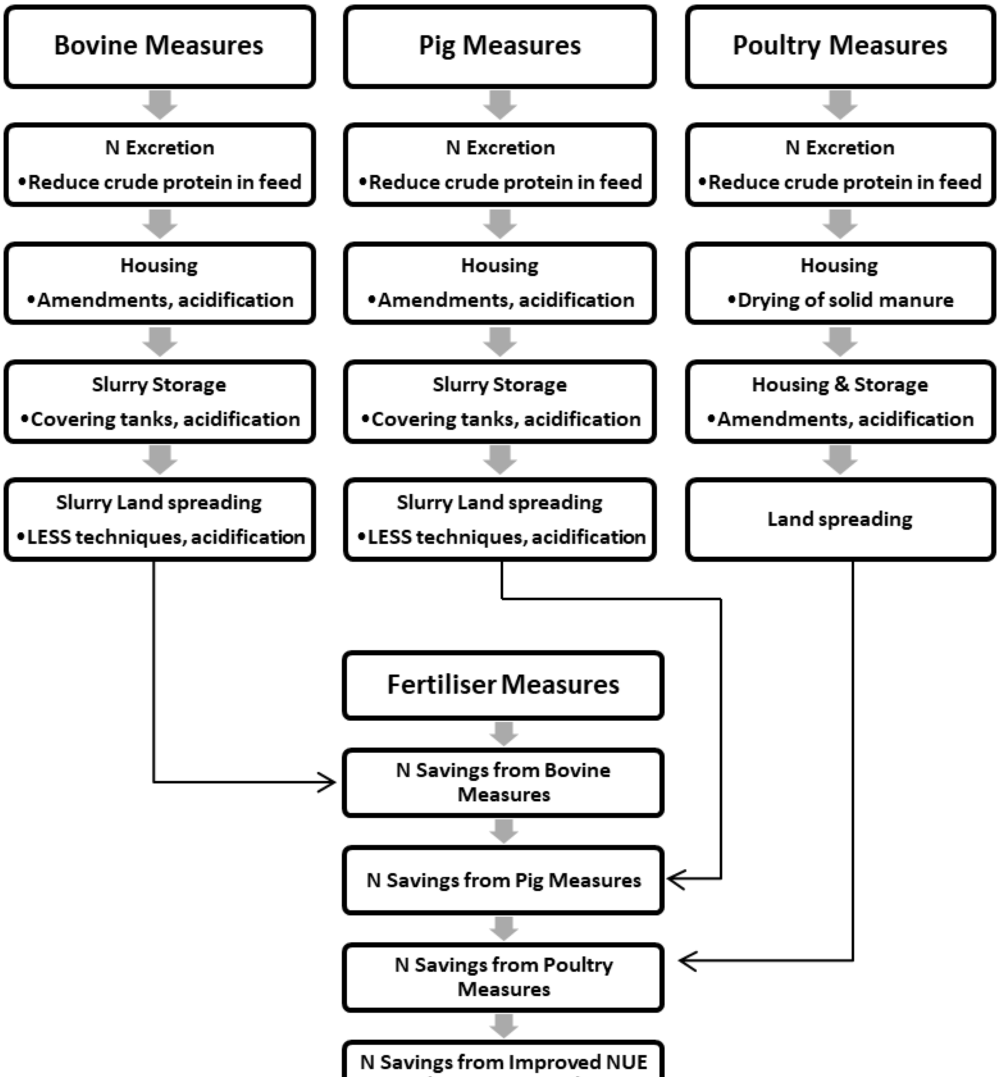
Overall, the three adoption rates were defined by two key aspects: i) the level of adoption projected for 2030 and ii) the speed at which that level would be achieved, represented by the slope of the adoption pathway. Appendix 2 provides a description of the assumptions around the technology adoption rates.

Appendices 3 and 4 provide a comprehensive overview of the NH_3 mitigation measures, technical details regarding the effectiveness of each abatement measure (Appendix 3) as well as its associated costs (Appendix 4). These measures were categorised into four groups: i) fertiliser measures, ii) bovine measures, iii) pig measures, and iv) poultry measures. Fertiliser measures include protected urea, establishing clover in grass swards and liming. Bovine and pig measures include, reducing crude protein content in concentrated feed, using additives for slurry storage, covered slurry storage and using LESS for manure spreading. Poultry measures include manure drying and applying manure additives. It's worth noting that sheep mitigation measures were not considered due to the extensive nature of many sheep production systems, which involve year-round grazing and thus may not require manure management. Additionally, fertiliser measures are already applicable to all animal systems.

Ammonia emissions occur at various stages of agricultural production, necessitating a strategic sequence of NH_3 abatement measures for overall emission reduction. In this analysis, all mitigation measures were applied in accordance with their order in the N flow framework (Figure 1) to consider potential interdependencies between them. This approach recognises that combining measures doesn't yield a straightforward additive effect in emissions reduction, as addressing NH_3 at an earlier stage may impact the volume of N availability for mitigation at later stages in the N flow chain.

Implementing abatement techniques upstream can lead to increased emissions downstream, as more N is retained within the system. For instance, using slurry additives reduces NH_3 losses during storage, preserving nitrogen. Conversely, conserving N throughout the manure management chain, including reduced crude protein intake in animal diets, ultimately lowers NH_3 emissions throughout the system. Moreover, enhancing the nitrogen use efficiency (NUE) of organic manures reduces the need for synthetic fertilisers, thereby lowering associated fertiliser-based emissions. Figure 1 below outlines the stages of the manure management chain targeted by the selected measures.

Figure 1: Conceptual N framework displaying the order of addition of ammonia mitigation measures to the marginal abatement cost analysis to account for the systems N flow.



3. Results

3.1: Marginal Abatement Cost Curve (MACC) Analysis

Tables 3, 4 and 5 illustrate the average ammonia abatement per year, average abatement cost per year and marginal abatement cost for the different scenarios modelled over the projection period.

Table 3: Average abatement, average cost and marginal abatement cost under S1 and low, moderate and high technology adoption rates

	S1L	S1M	S1H	S1L	S1M	S1H	S1L	S1M	S1H
	Average NH$_3$ abatement (kt) per annum (2022-2030)	**Average NH$_3$ abatement (kt) per annum (2022-2030)**	**Average NH$_3$ abatement (kt) per annum (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**€ per kg NH$_3$ abated**	**€ per kg NH$_3$ abated**	**€ per kg NH$_3$ abated**
Protected Urea	0.53	1.72	3.05	-3.24	-39.81	-8.93	-6.11	-23.20	-2.93
Clover	0.04	0.15	0.32	-0.49	-1.90	-3.93	-12.21	-12.29	-12.21
Liming	0.09	1.29	2.52	8.73	-3.12	-6.48	94.79	-2.41	-2.57
Crude Protein - Dairy	Not adopting	0.50	0.50	N/A	-3.05	-8.44	N/A	-6.17	-17.04
Amendments - Bovine	Not adopting	1.00	2.36	N/A	27.66	65.68	N/A	27.80	27.78
Covered Stores - Bovine	Not Increasing	0.84	0.94	N/A	-0.72	-0.34	N/A	0.67	-0.36
LESS Bovine	4.43	11.25	11.76	0.29	-3.68	12.39	0.06	-0.33	1.05
Crude Protein - Pigs	Not adopting	0.03	0.09	N/A	-0.71	-0.58	N/A	-20.77	-6.18
Covered Stores - Pig	Not Increasing	0.06	0.19	N/A	0.00	0.58	N/A	-0.06	3.00
Amendments - Pig Slurry	Not adopting	0.28	0.91	N/A	1.31	4.33	N/A	4.68	4.74
LESS - Pigs	0.20	0.35	0.37	-0.03	0.14	0.27	-0.14	0.39	0.74
Amendments - Poultry	Not adopting	0.13	0.22	N/A	1.53	4.66	N/A	30.73	21.66
Poultry Manure - Drying	Not adopting	0.07	0.12	N/A	1.40	4.26	N/A	34.70	35.18
Total	**5.30**	**17.67**	**23.35**	**5.25**	**-17.27**	**63.46**	**76.40**	**33.74**	**52.86**

Under S1 scenario, as summarised in Table 3 potential mitigation ranges from 5.30 to 23.35 (kt) per annum depending on adoption rates. And costs vary from €-17.27 to €63.46 per Kg NH3 abated. Furthermore, use of protected urea and establishment of clover are cost saving methods across all three adoption rates. Additionally liming and lowering of crude protein content in bovine and pigs concentrate diets is cost saving under medium and high adoption rates. Implementation of these cost negative measures could provide a potential cost saving upto €18.50 (low adoption rate), €64.84 (medium adoption rate) and €40.93 (high adoption rate) million per annum. For S1 scenario, combining the cost positive and negative measures indicates a net total cost for implementing all measures of €76.21 (low adoption rate), €33.74 (medium adoption rate), and €52.86 (high adoption rate), million per Kg of NH_3 abated.

Table 4: Average abatement, average cost and marginal abatement cost under S2 and low, moderate and high technology adoption rates

	S2L	S2M	S2H	S2L	S2M	S2H	S2L	S2M	S2H
	Average NH_3 abatement (kt) per annum (2022-2030)	**Average NH_3 abatement (kt) per annum (2022-2030)**	**Average NH_3 abatement (kt) per annum (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**€ per kg NH_3 abated**	**€ per kg NH_3 abated**	**€ per kg NH_3 abated**
Protected Urea	0.49	1.56	2.86	-3.05	-37.17	-8.30	-6.18	-23.84	-2.91
Clover	0.04	0.15	0.32	-0.49	-1.90	-3.93	-12.21	-12.29	-12.21
Liming	0.09	1.29	2.52	8.73	-3.12	-6.48	94.79	-2.41	-2.57
Crude Protein - Dairy	Not adopting	0.48	0.48	N/A	-3.05	-8.19	N/A	-6.35	-17.03
Amendments - Bovine	Not adopting	0.81	2.27	N/A	26.36	62.62	N/A	32.42	27.60
Covered Stores - Bovine	Not Increasing	0.80	0.89	N/A	-0.68	0.69	N/A	0.75	0.77
LESS Bovine	3.57	10.51	10.99	-0.17	-3.38	11.66	-0.05	-0.32	1.06
Crude Protein - Pigs	Not adopting	0.03	0.09	N/A	-0.70	-0.58	N/A	-20.79	-6.17
Covered Stores - Pig	Not Increasing	0.06	0.19	N/A	0.00	0.57	N/A	-0.06	3.00
Amendments - Pig Slurry	Not adopting	0.27	0.90	N/A	1.29	4.28	N/A	4.68	4.74
LESS - Pigs	0.14	0.44	0.37	0.01	0.20	0.27	0.10	0.32	0.74
Amendments - Poultry	Not adopting	0.12	0.20	N/A	1.43	4.36	N/A	31.36	21.66
Poultry Manure - Drying	Not adopting	0.07	0.12	N/A	1.31	3.65	N/A	34.70	34.70
Total	**4.33**	**16.60**	**22.20**	**5.02**	**-19.41**	**60.61**	**76.45**	**38.17**	**53.38**

Table 4 shows that, under S2 scenario, potential mitigation ranges from 4.33 to 22.20 (kt) per annum depending on adoption rates. And costs vary from €-19.41 to €60.61 per kg NH3 abated. Similar to S1 scenario, protected urea and establishment of clover are cost saving methods across all three adoption rates while liming and lowering of crude protein content in bovine and pigs concentrate diets is cost saving under medium and high adoption rates. Implementation of these cost negative measures could provide a potential cost saving upto €18.39 (low adoption rate), €65.68 (medium adoption rate) and €40.89 (high adoption rate) million per annum. For S2 scenario, combining the cost positive and negative measures indicates a net total cost for implementing all measures of €76.45 (low adoption rate), €38.17 (medium adoption rate), and €53.38 (high adoption rate), million per Kg of NH3 abated.

Table 5: Average abatement, average cost and marginal abatement cost under S3 and low, moderate and high technology adoption rates

	S3L	S3M	S3H	S3L	S3M	S3H	S3L	S3M	S3H
	Average NH_3 abatement (kt) per annum (2022-2030)	**Average NH_3 abatement (kt) per annum (2022-2030)**	**Average NH_3 abatement (kt) per annum (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**Average cost per annum (€ million) (2022-2030)**	**€ per kg NH_3 abated**	**€ per kg NH_3 abated**	**€ per kg NH_3 abated**
Protected Urea	0.57	1.77	3.21	-3.47	-42.26	-9.47	-6.13	-23.82	-3.10
Clover	0.04	0.15	0.32	-0.49	-1.90	-3.93	-12.21	-12.29	-12.21
Liming	0.09	1.29	2.52	8.73	-3.12	-6.48	94.79	-2.41	-2.57
Crude Protein - Dairy	Not adopting	0.52	0.52	N/A	-3.21	-8.83	N/A	-6.20	-17.07
Amendments - Bovine	Not adopting	1.20	2.56	N/A	29.17	67.42	N/A	24.40	26.31
Covered Stores - Bovine	Not Increasing	0.88	0.98	N/A	-0.76	-0.37	N/A	0.59	-0.37
LESS Bovine	4.87	12.07	13.22	0.44	-4.00	12.70	0.09	-0.33	1.25
Crude Protein - Pigs	Not adopting	0.03	0.09	N/A	-0.71	-0.58	N/A	-20.77	-6.21
Covered Stores - Pig	Not Increasing	0.13	0.19	N/A	-0.05	0.58	N/A	-0.41	3.00
Amendments - Pig Slurry	Not adopting	0.28	0.91	N/A	1.31	4.33	N/A	4.68	4.74
LESS - Pigs	0.20	0.35	0.37	-0.03	0.14	0.27	-0.14	0.39	0.74
Amendments - Poultry	Not adopting	0.13	0.21	N/A	1.53	4.66	N/A	30.73	21.66
Poultry Manure - Drying	Not adopting	0.07	0.13	N/A	1.40	4.64	N/A	34.70	34.70
Total	**5.77**	**18.88**	**22.21**	**5.18**	**-22.44**	**64.92**	**76.40**	**29.26**	**50.86**

As summarised in Table 5 Under S3 scenario, potential mitigation ranges from 5.77 to 22.20 (kt) per annum depending on adoption rates. And costs vary from €-22.44 to €64.92 per kg NH3 abated. Similar to S1 and S2 scenarios, protected urea and establishment of clover are cost saving methods across all three adoption rates while liming and lowering of crude protein content in bovine and pigs concentrate diets are cost saving under medium and high adoption rates. Implementation of these cost negative measures could provide a potential cost saving up to €18.34 (low adoption rate), €65.5 (medium adoption rate) and €41.25 (high adoption rate) million per annum. For S3 scenario, combining the cost positive and negative measures indicates a net total cost for implementing all measures of €76.40 (low adoption rate), €29.26 (medium adoption rate), and €50.63 (high adoption rate), million per Kg of NH3 abated.

However, these costs and savings are predicated on efficiency gains driven by best management practice adoption, with associated reductions in chemical N fertiliser application. If farmers do not adjust management practices (e.g. chemical fertiliser application rates) to reflect efficiency gains achieved through implementation of mitigation measures, then the level of ammonia abatement would be lower than anticipated in this analysis.

3.2 Combined impact of mitigation measures to 2030

3.2.1. Emissions with Business-as-usual scenario and three technology adoption rates

Figure 2 below outlines the aggregate emissions using the EPA national emission inventory model (Hyde et al., 2022) for the agricultural sector in Ireland under the S1 activity level scenario with low, medium and high adoption rates. The yellow line reflects the NH_3 emission targets as set down under the EU NEC Directive 2016/2284 for each year.

Figure 2: NH_3 Emissions under Business as Usual scenario (S1)

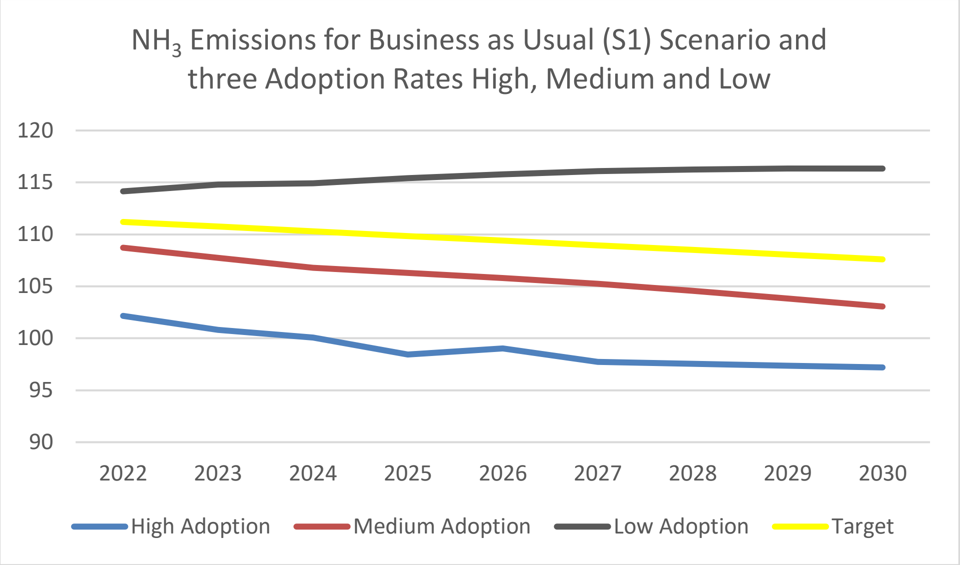
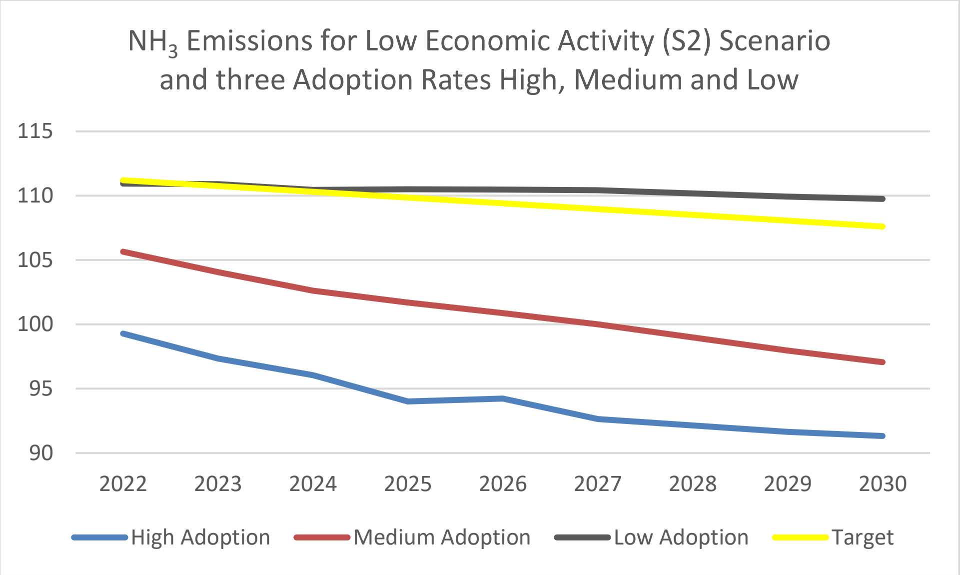


Figure 2 illustrates that, under the S1 scenario (business-as-usual) achieving emission reduction targets for Ireland is possible with high and medium levels of mitigation measure adoption rates. However, continuing with low adoption rates would result in NH_3 emissions not meeting targets by 2030.

3.2.2. Emissions with Low Activity scenario (S2) and three technology adoption rates

Similar to the results under S1, Figure 3 shows that under S2 emission reduction targets are met with high and medium levels of mitigation measure adoption rates. However, if the low technology adoption rate were to continue then ammonia emissions would exceed the target limits, with the difference between emissions and the target increasing year on year towards 2030.

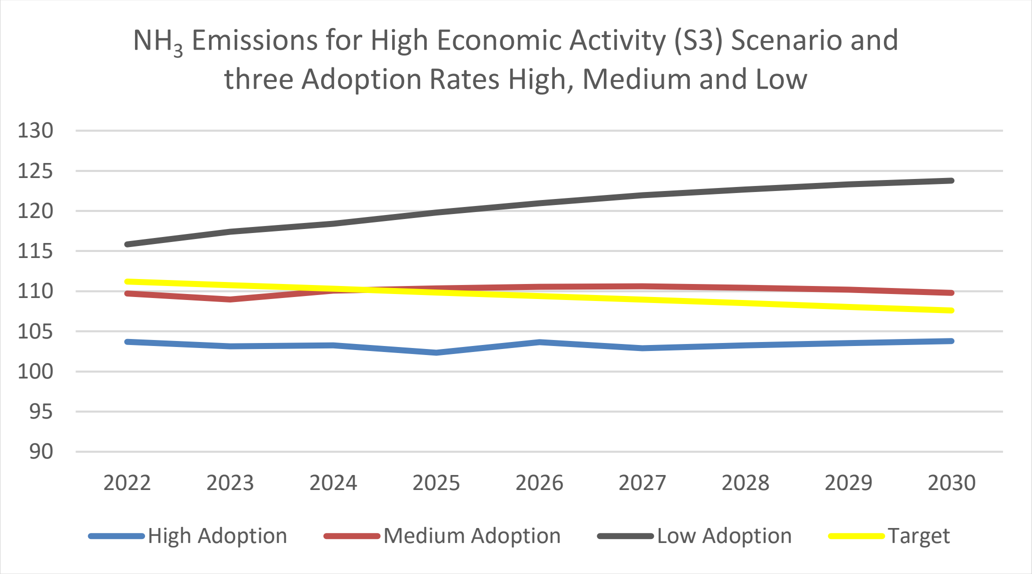
Figure 3: Total NH3 Emissions under Low economic activity (S2) scenario and three technology adoption rates



3.2.3. Emissions with High Activity scenario (S3) and three technology adoption rates

As shown in figure 4 if higher activity levels were to prevail in Ireland from 2022 to 2030, then the reduction targets cannot be achieved under the low or medium technology adoption rates assumed in this analysis.

Figure 4: Total NH_3 Emissions under High economic activity (S3) scenario and three technology adoption rates



According to Figure 4, NH_3 emission under low, medium and high technology adoption rates exceeds the target in 2030.

4. Discussion

The estimated ammonia emissions reduction outlined in this study depends on mitigation measure adoption rates, projected agricultural activity levels and emissions factors. The results here estimate NH_3 abatement potential with high adoption rates for the mitigation pathways at 23.35 (S1), 22.20 (S2) and 25.25 (S3) kilotonnes of NH_3 during the study period and 17.67 (S1), 16.60 (S2) and 18.88 (S3) kilotonnes of NH_3 with medium technology adoption rates. This is significantly higher than the mitigation potentials estimated in the previous ammonia abatement analyses of between 10.6 and 12.05 kilotonnes NH3 per annum (Lanigan et al., 2015) and 15.26 kt NH_3 (Buckley et al., 2020). In contrast, under the low adoption rate scenarios the NH_3 abatement potential was 5.30 (S1), 4.33 (S2), and 5.77 (S3).

The findings highlight the substantial impact of differing assumptions about future agricultural activity on the emissions projections, adoption rates and abatement potential before factoring in mitigation measures. These uncertainties are crucial when evaluating Ireland's capacity to meet ammonia emission reduction targets. the extent of these will determine if targets can be achieved or at least close to target.

The adoption of best management practices among farmers have historically occurred in gradual increments, extending over several years rather than in sudden changes (Rogers, 1995). However, Ireland has seen strong adoption rates recently for low-emission slurry spreading due to the implementation of Nitrates Directive-based GAP regulations[2]. Achieving the high and ambitious adoption rates hypothesised in this analysis would likely require either further Government mandate (stick) or incentives (carrot). Addressing adoption rates also

---

[2] Farming under Nitrates derogation scheme allows a higher stocking rate in farms and regulates the spreading method of manure i.e. Low Emission Slurry Spreading Equipment must be used by the participating farmers.

involves inherent uncertainties, with studies employing various approaches, including maximum theoretical adoption, maximum biophysical adoption, or linear/non-linear uptake rates (Moran et al., 2010; Pellerin et al., 2018; Eory et al., 2016; Lanigan et al., 2018). This study assumed a mix of linear and exponential adoption rates as well as zero adoption rates for uncommon technologies. Teagasc NFS survey data (2015-2021) were reviewed to determine specific historic adoption rates of relevant technologies examined here.

In Ireland, meeting ammonia (NH_3) emission reduction commitments pose a challenge, but it's not unique. Other EU countries including Denmark, France, and Germany are also grappling with similar issues, particularly in the context of livestock farms and manure management (Hyde et al., 2022).

In France, the focus is on reducing NH_3 emissions by implementing low-emission slurry spreading and immediate incorporation of manures on arable land (Martin & Mathias, 2013). Denmark, with its dominant pig and poultry operations, emphasise measures like low-emission housing, air scrubbing, slurry acidification, slurry cooling, tank covering, and adjusted feeding practices (Gyldenkærne and Mikkelsen, 2007; Jacobsen and Ståhl, 2017

While Lenerts et al. (2021) follow a similar methodology to that used in this Irish study, their assumptions relating to adoption rates for individual measures present large uncertainty. For instance, Martin and Mathias (2013) assumed 100% adoption rates for measures in their study. Conversely, Pellerin et al. (2013) applied three different sigmoidal profile curves to describe uptake, with the uptake profile dependent on the maximal abatement potential of each measure and the point at which the rate of adoption accelerates.

Typically, public policy assesses the effectiveness of individual mitigation measures to prioritise cost-effective options. However, adopting measures at one stage of manure management can affect the effectiveness of measures further down the chain because failing to mitigate NH_3 emissions during the land spreading phase can nullify prior mitigation efforts. For example, adopting a lower crude protein content reduces overall NH_3 production. Due to the adoption of covered slurry stores and slurry amendments, more N is retained, and N losses are avoided, but these benefits could be diluted at the land-spreading stage if a conventional splash plate broadcast method is used. Implementing individual measures may suggest a potential reduction in NH_3 emissions. However, this potential can only be fully realised if complementary best practices, like the LESS land spreading method, are also adopted concurrently.

Furthermore, the choice of fertiliser plays a pivotal role in NH_3 emissions. Protected Urea reduces NH_3 emissions compared to Calcium Ammonium Nitrate (CAN), but it also affects nitrous oxide emissions (Hyde et al., 2022). Therefore, comprehensive gaseous emissions mitigation should consider various factors to avoid unintended consequences. In the current analysis, employment of LESS for bovine manure application was able to deliver 60% of the overall mitigation in Irish agriculture.

It's worth noting that there are variations in emission factors between Urea and nitrate-based fertilisers (Hyde et al., 2022). Replacing Urea with protected Urea results in a significant reduction in NH_3 emissions. However, transitioning from Calcium Ammonium Nitrate (CAN) to protected urea can lead to increased NH_3 emissions. Additionally, CAN fertiliser application on managed agricultural soils generates higher GHG emissions, particularly N_2O gas, than protected urea. Therefore, substituting CAN with protected urea is a favourable strategy from a GHG mitigation perspective (Lanigan et al., 2018). To effectively mitigate gaseous emissions, it is essential to adopt a holistic approach to prevent pollution swapping. Enhanced fertilisers like protected urea offer multiple benefits, reducing emissions while maintaining crop yields (Harty et al., 2016; Watson et al., 2009; Harty et al., 2017).

Furthermore, improving our understanding of the efficacy of these new measures and quantifying country-specific emission factors is essential. National emission inventories will need refinement to incorporate these new mitigation measures effectively. Additionally, considering the synergistic or antagonistic relationship between GHG and NH_3 mitigation, country-specific data will help identify actions that optimise the mitigation potential of both GHG and NH_3. The possibility of higher-tier reporting, including spatially detailed NH_3 emissions modelling, could be explored in the future to account for abiotic factors such as weather and soil type.

The successful realisation of ammonia (NH_3) mitigation potential hinges on the actual adoption of mitigation strategies by Irish farmers. Various barriers have been identified that affect the adoption of these measures, including cost, knowledge and awareness levels, the ability to employ certain technologies at the farm level, individual farm-specific constraints, and the availability of equipment or raw materials needed for mitigation actions (Moerkerken et al., 2020). To achieve the full potential of NH_3 mitigation, it is essential to gain a deeper understanding of these barriers hindering the uptake of mitigation measures. However, conducting research alone will not be sufficient to achieve this mitigation potential. It requires strong linkages to extension services that provide farmers with the knowledge and guidance needed to identify and implement suitable solutions for their individual farms. The process of knowledge transfer and co-creation of mitigation measures has long been recognised as critical in maximising the adoption of these measures and realising the identified mitigation potentials (Rogers, 1995).

5. Conclusions

Results from this analysis indicate that the high and medium adoption rates outlined here will allow Ireland to mitigate an amount of NH_3 sufficient to comply with emission reduction commitments (conditional on the assumed measure uptake) under the S1 (business as usual), S2 (lower) and S3 (higher) activity level scenarios. With further emissions reductions already agreed beyond 2030, the adoption of technologies that mitigate ammonia emissions will be of ever greater importance and the role of policy in facilitating this adoption will come under greater scrutiny.

Acknowledgements

The authors wish to thank experts in and outside Teagasc for their contribution to the selection of mitigation measures and assistance with detailing adoption scenarios included in this analysis.

Funding

Abating Ammonia in Agriculture (AAA) (funding call: 2019R554) is a large project funded by the Department of Agriculture, Food and the Marine (DAFM) in Ireland.

Disclosure statement

The authors report there are no competing interests to declare.

References

Bailey, J.S., (1997). Some influences of initial sward botanical composition on the responsiveness of Irish grassland to liming. Irish J. Agr. Food Res. 36, 161–173.

Bergin, A., Duffy, D., Foley, D., Garcia-Rodrigues, A., Lawless, M., McInerney, N., Morgenroth, E., McQuinn, K., (2016). Ireland's Economic Outlook: Perspectives and Policy Challenges https://www.esri.ie/system/files?file=media/file-uploads/2016-12/CB201617.pdf last accessed 20.05.2022

Binfield, J.C.R., Donnellan, T., Hanrahan, K., (2008). An Examination of Milk Quota expansion at EU member State Level with specific emphasis on Ireland. 107th EAAE Seminar "Modelling of Agricultural and Rural Development Policies", Seville, Spain, January 29th -February 1st.

Binfield, J.C.R., Donnellan, T., Hanrahan, K., Hart, C., Westhoff, P., 2004. CAP Reform and the WTO: Potential Impacts on EU Agriculture. . American Agricultural Economics Association Annual Meeting, Denver, Colorado, July 1-4.

Binfield, J.C.R., Donnellan, T., Hanrahan, K., Westhoff, P., 2003. The Luxembourg CAP Reform Agreement: Implications for EU and Irish Agriculture. In The Luxembourg CAP Reform Agreement: Analysis of the Impact on EU and Irish Agriculture, FAPRI-Ireland Report. Teagasc.

Bittman, S., Dedina, M., Howard C.M., Oenema, O., Sutton, M.A., (2014). Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen. Centre for Ecology and Hydrology, Edinburgh, UK.

Burchill, W., (2019). To advance the knowledge of good grassland management in Irish farming. Members' Information Booklet. Irish Grassland Association pp. 28–29.

Burchill, W., James, E.K., Li, D., Lanigan, G.J., Williams, M., Iannetta, P.P.M., Humphreys, J., 2014. Comparisons of biological nitrogen fixation in association with white clover (Trifolium repens L.) under four fertiliser nitrogen inputs as measured using two 15N techniques. Plant and Soil 385, 287–302.

Burchill, W., Lanigan, G.J., Li, D., Williams, M., Humphreys, J., 2016. A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions. Agriculture, Ecosystems and Environment 220, 202–210.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil/plant system: A review. Annals of Applied Biology 162, 145-173.

CSO, 2022. Fertiliser Prices. https://www.cso.ie/en/releasesandpublications/ep/p-syi/statisticalyearbookofireland2020/agri/agricultureaccountsprices/ last accessed 20.05.2022

Culleton, N., Murphy, W., Coulter, B., 1999. Lime in Irish agriculture. Fertiliser Association of Ireland, Winter Scientific Meeting. UCD, Dublin. Publication, pp. 28–48.

DAFM, 2020. Ag Climatise - A Roadmap towards Climate Neutrality. https://www.gov.ie/en/publication/07fbe-ag-climatise-a-roadmap-towards-climate-neutrality/# last accessed 20.05.2022

de Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J.C., Louwagie, G., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Sci. Total Environ. 786, 147283.

Donnellan, T., Hanrahan, K., 2006. The impact of potential WTO trade reform on greenhouse gas and ammonia emissions from agriculture: A case study of Ireland. In: Swinnen, J., Kaditi, E. (Eds.), Trade Agreements and Multifunctionality, Centre for European Policy Studies, Brussels, Belgium.

Donnellan, T., Hanrahan, K., 2021. Teagasc Agricultural Activity Projections (2019). Memo Teagasc. December 2019.

EC, (2016). Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC.

EC, (2021). EU Agricultural Outlook. For markets, income and environment 2021 – 2031. https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/agricultural-outlook-2021-report_en.pdf last accessed 20.05.2022

EMEP/EEA, 2019. Air Pollutant Emission Inventory Guidebook 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019 last accessed 20.05.2022

EPA, (2022). Ireland's Air Pollutant Emissions 1990-2030. https:// www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Air-Pollutant-Emissions-Report-2022. Last accessed 20.10.2023

EPA, 2023. Ireland's Air Pollutant Emissions 1990-2030. https:// https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-air-pollutant-emissions-2021-1990-2030. Last accessed 20.10.2023

Eurostat, (2021a). Air pollutants by source sector https://ec.europa.eu/eurostat/databrowser/view/ENV_AIR_EMIS__custom_1727452/default/table?lang=en last accessed 20.05.2022

Eurostat, 2021b. Ammonia emissions from agriculture - % of total emissions https://ec.europa.eu/eurostat/databrowser/view/tai07/default/table?lang=en last accessed 20.05.2022

FCI, 2020. The Association of Farm and Forestry Contractors in Ireland Contracting Charges Guide 2020. https://www.agriland.ie/farming-news/table-contractor-association-releases-full-2020-guide-rates/ last accessed 20.05.2022

Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G., Chambers, B.J., Richards, K.G., 2016. Ammonia emissions from Urea, stabilised Urea and calcium ammonium nitrate: insights into loss abatement in temperate grassland. Soil Use Manage. 32, 92-100.

Gyldenkærne, S., Mikkelsen, M.H., 2007. Projection of the Ammonia Emission from Denmark from 2005 until 2025. University of Aarhus, Denmark. https://www2.dmu.dk/pub/ar239.pdf last accessed 20.05.2022

Hanrahan, K., 2001. The EU GOLD MODEL 2.1, An introductory manual, Working Paper, AG-MEMOD. Memo Teagasc.

Harty, M.A., Forrestal, P.J., Carolan, R., Watson, C.J., Hennessy, D., Lanigan, G.J., Wall, D.P., Richards, K.G., 2017. Temperate Grassland Yields and Nitrogen Uptake Are Influenced by Fertilizer Nitrogen Source. Agron. J. 109, 71-79.

Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D., Laughlin, R.J., Richards, K.G., Lanigan, G.J., 2016. Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to Urea based formulations. Sci. Total Environ. 563, 576-586.

Hristov, A.N., 2011. Contribution of ammonia emitted from livestock to atmospheric fine particulate matter (PM2. 5) in the United States. J. Dairy Sci. 94, 3130-3136.

Humphreys, J., 2020. Personal communication.

Hyde, B., 2020. Personal communication.

Hyde, B., Duffy, D., Ryan, A.M., Murphy, J., Fahey, D., Monaghan, S., Kehoe, A., 2022. Ireland Informative Inventory Report 2022. Air pollutant emissions in Ireland from 1990–2020 were reported to the secretariat of the UNECE convention on long-range transboundary air pollution and to the European Union.

Jacobsen, B.H., Stáhl, L., 2017. Economic analysis of the ammonia regulation in Denmark in relation to the Habitat Directive. Department of Food and Resource Economics (IFRO), University of

Copenhagen. https://ifro.ku.dk/english/events/pastevents/2017/ammoniakregulering-af-husdyrproduktionen/Economic_analysis_of_Nature_2000_regulation_in_Denmark_final_21-11-2017.pdf last accessed 20.05.2022

Kavanagh, I., Burchill, W., Healy, M.G., Fenton, O., Krol, D.J., Lanigan, G.J., 2019. Mitigation of ammonia and greenhouse gas emissions from stored cattle slurry using acidifiers and chemical amendments. Journal of Cleaner Production 237.

Lanigan, G., Donnellan, T., Hanrahan, K., Carsten, P., Shalloo, L., Krol, D., Forrestal, P.J., Farrelly, N., O'Brien, D., Ryan, M., 2018. An analysis of abatement potential of Greenhouse Gas emissions in Irish agriculture 2021-2030. Teagasc.

Lanigan, G.J., Donnellan, T., Hanrahan, K., Burchill, W., Forrestal, P., McCutcheon, G., Crosson, P., Murphy, P., Schulte, R., Richards, K., 2015. An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture to 2030. Teagasc Submission to the Department of Agriculture, Food and the Marine. Teagasc, Oak Park, Carlow.

Lawlor, P., 2020. Personal communication.

Lenerts, A., Naglis-Liepa, K., Popluga, D., Kreišmane, D., Aplociņa, E., Bērziņa, L., Frolova, O., 2021. Marginal abatement cost curve for an ammonia reduction measure in agriculture: the case of Latvia. Agronomy Research 19, 1575-1585.

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric. Syst. 103, 198-209.

Martin, E., and Mathias, E., 2013. Analysis of the potential of 10 practices for reducing ammonia emissions from French livestock farms by 2020 and 2030– Summary. ADEME, Angers, France.

Misselbrook, T.H., Sutton, M.A. and Scholefield, D. (2006) 'A simple process-based model for estimating ammonia emissions from agricultural land after Fertilizer Applications', *Soil Use and Management*, 20(4), pp. 365–372. doi:10.1111/j.1475-2743.2004.tb00385.x.

Mkhonza, N.P., Buthelezi-Dube, N.N., Muchaonyerwa, P., 2020. Effects of lime application on nitrogen and phosphorus availability in humic soils. Scientific Reports 10.

Moerkerken, A., Blasch, J., van Beukering, P., van Well, E., 2020. A new approach to explain farmers' adoption of climate change mitigation measures. Clim. Change 159, 141-161.

Moore Jr, P.A., Daniel, T.C., Edwards, D.R., 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. Journal of Environmental Quality, pp. 37-49.

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A., 2010. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. Journal of Agricultural Economics 62, 93-118.

National Parks and Wildlife Service, 2019. The Status of EU Protected Habitats and Species in Ireland. Dublin, Ireland. https://www.npws.ie/sites/default/files/publications/pdf/NPWS_2019_Vol1_Summary_Article17.pdf last accessed 20.05.2022

O'Brien, D., Shalloo, L., 2019. A Review of Livestock Methane Emission Factors (2016-CCRP-DS.11). EPA Research Report No. 288. https://www.epa.ie/publications/research/climate-change/Research_Report_288.pdf last accessed 20.05.2022

OECD, 2015. Aglink-Cosimo Model Documentation: A partial equilibrium model of world agricultural markets. Paris. https://www.agri-outlook.org/documents/Aglink-Cosimo-model-documentation-2015.pdf last accessed 20.05.2022

Oenema, O., Witzke, H.P., Klimont, Z., Lesschen, J.P., Velthof, G.L., 2009. Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture, Ecosystems and Environment 133, 280-288.

Patton, J., 2020. Personal communication.

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.P., Chenu, C., Colnenne-David, C., de Cara, S., Delame, N., 2013. How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures. [Technical Report].

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. Environmental Science and Policy 77, 130-139.

Phelan, P., Keogh, B., Casey, I.A., Necpalova, M., Humphreys, J., 2012. The effects of treading by dairy cows on soil properties and herbage production for three white clover-based grazing systems on a clay loam soil. Grass Forage Sci. 68, 548-563.

Ragnauth, S.A., Creason, J., Alsalam, J., Ohrel, S., Petrusa, J.E., Beach, R.H., 2015. Global mitigation of non-CO2 greenhouse gases: marginal abatement costs curves and abatement potential through 2030. Journal of Integrative Environmental Sciences 12, 155-168.

Reis, S., Howard, C., Sutton, M., 2015. Costs of Ammonia Abatement and the Climate Co-Benefits. Springer Media V.B. , Dordrecht. ISBN 978-94-017-9722-1

Rogers, E. M. (1995). Diffusion of innovations, fourth edition, New York, Free Press of Glencoe. USA

Smith, P., Martino, D., Cai, Z.C., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G.X., Romanenkov, V., Schneider, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture Ecosystems & Environment 118, 6-28.

Stokstad, E., 2014. Ammonia pollution from farming may exact hefty health costs. American Association for the Advancement of Science.

Teagasc, 2020. Teagasc Soil Services. https://www.teagasc.ie/crops/soil--soil-fertility/soil-analysis/teagasc-soil-services/ last accessed 13.05.2022

UNECE, 2020. Assessment Report on Ammonia – 2020. https://unece.org/fileadmin/DAM/env/documents/2020/AIR/WGSR/Final_Assessment_Report_on_Ammonia_v2_20201126_b.pdf last accessed 13.05.2022

Wall, D., 2020. Personal communication.

Watson, C.J., Laughlin, R.J., McGeough, K.L., 2009. Modification of nitrogen fertilisers using inhibitors: Opportunities and potentials for improving nitrogen use efficiency. International Fertiliser Society, York, UK, pp. 1-40.

Webb, J., Menzi, H., Pain, B.F., Misselbrook, T.H., Dämmgen, U., Hendriks, H., Döhler, H., 2005. Managing ammonia emissions from livestock production in Europe. Environ. Pollut., pp. 399-406.

Westhoff, P., Meyers, W.H., 2010. The FAPRI approach: A few key principles. International Agricultural Trade and Development: New Research, pp. 133-135.

Xu, R., Tian, H., Pan, S., Prior, S.A., Feng, Y., Batchelor, W.D., Chen, J., Yang, J., 2019. Global ammonia emissions from synthetic nitrogen fertiliser applications in agricultural systems: Empirical and process-based estimates and uncertainty. Glob. Change Biol. 25, 314-326.

Zhang, X., Gu, B., van Grinsven, H., Lam, S.K., Liang, X., Bai, M., Chen, D., 2020. Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. Nature Communications 11.

Appendix 1: Economic Activity Levels

Bovine population and chemical N sales projections for year 2030

	Year	S1	S2	S3
Total bovine population (million)	2022	7.19	6.9	7.2
	2030	7.09	6.6	7.6
Dairy cow (million, annual average population)	2022	1.54	1.52	1.5
	2030	1.63	1.56	1.7
Other cow (million, annual average population)	2022	0.93	0.90	0.99
	2030	0.75	0.68	0.90
Chemical N sales (thousand tonnes)	2022	366.2	348.4	374.6
	2030	397.7	370.9	431.4

Note: In 2022, Ireland had a total cattle population of 7.4 million, with 1.6 million being dairy cows (Clarke, 2022), and N fertiliser sales amounted to 343,193 tonnes (CSO, 2022)

Appendix 2 : Assumptions for technology adoption rates

Mitigation measure	**Low Adoption**	**Medium Adoption**	**High adoption**
Fertiliser measures			
Protected Urea	30% urea, and 20% CAN and compound fertiliser replaced in 2024	60% of urea and 30% of CAN and compound fertilisers replaced 2024	100% urea and 65% CAN and compound fertiliser replaced by 2027 (AgClimatise, 2020).
Clover Intensive dairy farms apply more than 165 Kg N fertiliser per Ha	1% of intensive dairy farms to establish clover each year, reaching 15% of the lands in 2030	4% of intensive dairy farms (farms that apply 165 Kg N fertiliser per Ha) to establish clover each year reaching 40% of the lands in 2030	8% of intensive dairy farms (farms that apply 165 Kg N fertiliser per Ha) to establish clover each year reaching 80% of the lands in 2030
Liming1920 million hectares (47%) of the grassland soils have suboptimum pH levels in 2022x. Application rates of 7.5 tonnes per hectare for the initial application and then 5 tonnes per hectare maintenance rate. Re-liming for maintenance is after 4 years of initial application.	0.29-0.67Mtonnes of lime applied, 2% of suboptimal lands newly limed annually.	1-1.1Mtonnes of lime applied, 7% of suboptimal lands newly limed annually.	2Mtonnes of lime applied from 2022 to 2030 (AgClimatise, 2020), 14% of suboptimal lands newly limed annually.
Bovine measures			
Low emission slurry spreading - LESS	30% of slurry type manure applied using LESS	Increasing from 62% (2022) to 90% in 2030 at 3.5% per year increasing rate	Increasing from 62% (2022) to 90% in 2027 (AgClimatise, 2020), 30% by TH , 70% by TS.
Covering slurry stores	Unchanged at 93%	increase from 93% to 96% annually stepwise (0.375% per year)	Increasing from 94% in 2022 to 100% in 2027 (AgClimatise, 2020).
Reducing crude protein content of diet	Unchanged at 0%	Increasing from 10% in 2022 to 50% in 2030	Increasing from 60%-90% in 2025 and remain at 90% to 2030
Slurry amendments	Unchanged at 0%	Increasing from 10% in 2022 to 50% in 2030	Increasing from 60% in 2025, increased to 90% in 2024
Pigs measures			

Low emission slurry spreading - LESS	1% increase annually reaching 40% to 48% in 2030	increasing from 62% to 90%, 3.5% per year	Increasing from 62% (2022) to 90% in 2027 (AgClimatise, 2020). 30% by TH , 70% by TS.
Reducing crude protein content of diet. Currently the crude protein levels of the weaner, finisher stage 1 and stage 2 feed is assumed to be 20%, 18.7% and 18%. This pathway assumes reducing crude protein by 1, 2 and 2 percentage points for the weaner, finisher stage 1 and stage 2, respectively	Unchanged at 0%	Increasing adoption from 10% in 2022 to 50% in 2030	Increasing adoption from 60% in 2022 increase to 90% in 2025
Covering slurry stores	Unchanged at 88%, from 2022 to 2030.	88% to 91% in 2030, 0.375% per year	Increasing from 92% to 95%
Slurry amendments (alum compound)	Unchanged at 0%	Increasing from 0% to 50%, 6.25% per year rate	Increasing from 60%-90% in 2025 and remain at 90% to 2030.
Poultry measures			
Drying of poultry manure	Unchanged at 0%	Increasing from 0% to 50%, 6.25% per year rate	Increasing from 60%-80% in 2025 and remain at 80% to 2030
Poultry manure amendments	Unchanged at 0%	Increasing from 0% to 50%, 6.25% per year rate	Increasing from 60%-80% in 2025 and remain at 80% to 2030

Appendix 3: Level of efficacy of the selected measures

Mitigation measure	Efficacy measurement	Reference
Fertiliser measures		
Protected Urea (Urea with urease inhibitor)	Approximately 78.5% reduction in emissions compared to straight Urea.	EEA/EMEP Guidebook, 2019 - straight urea emission factor; Forrestal et al., 2016 - protected urea emission factor.
Clover	Inclusion of clover in grass sward increases biological nitrogen fixation by 80 kg N ha^{-1} yr^{-1} and hence allows a reduction in synthetic fertiliser input.	Burchill et al., 2014; Phelan, 2012.
Liming	Optimisation of soil pH increases nitrogen mineralisation by 70 kg N ha^{-1} yr^{-1} and hence allows a reduction in synthetic fertiliser input accordingly.	Nyborg and Hoyt, 1978; Bailey, 1997; Culleton et al., 1999; Mkhonza et al., 2020.
Bovine measures		
Low emission slurry spreading – LESS	Adoption of trailing hose and trailing shoe methods provide 30% and 60% reduction in emission respectively, compared to splashplate method.	Bittman et al., 2014.
Covering slurry stores	Floating materials, flexible covers and rigid/ tight covers provide 40%, 60% and 80% reduction in emission compared to uncovered stores, respectively. Average 50% reduction assumed here.	Reis et al, 2015; EEA/EMEP Guidebook, 2019 - uncovered store emission factor 10%, covered store 5%.
Reducing crude protein content of diet	1 percentage point reduction in crude protein of dairy concentrates. This leads to a reduction in the nitrogen excretion rate of dairy cows by 1.5 kg.	O'Brien & Shalloo, 2019.
Slurry amendments	Various chemical acidifiers reduce emissions during storage by up to 96%. Here, efficacy of 70% is assumed for allum	Kavanagh et al. 2019.
Pigs measures		
Low emission slurry spreading – LESS	Adoption of trailing hose and trailing shoe methods provide 30% and 60% reduction in emission compared to splash plate, respectively	Bittman et al., 2014
Reducing crude protein content of diet	1 percentage point reduction in crude protein of pig concentrates reduces nitrogen excretion rate of pigs by 1.4%	Hyde, 2020.
Covering slurry stores	Approximately 75% reduction in emissions compared to uncovered stores based on standard emission factors.	EEA/EMEP Guidebook, 2019 - uncovered store emission factor of 52%, covered store EF of 13%
Slurry amendments	Various chemical acidifiers reduce emissions during storage by up to 96%. Here, efficacy of 70% is assumed	Kavanagh et al. 2019.
Poultry measures		
Drying of poultry manure	Drying treatment reduces emissions by approximately 40%.	Reis et al, 2015.

Poultry manure amendments	Addition of alum to poultry manure reduces emissions by approximately 30%.	Moore et al., 2000.

Appendix 4: Cost assumptions

Mitigation measure	Cost measurement	Reference
Protected Urea (Urea with urease inhibitor)	Based on quantities and cost of fertiliser modelled to 2030 as baseline vs adoption pathway. Cost estimate takes account of reduced fertiliser use due to increased NUE associated with low-emitting fertiliser.	Wall, 2020; DAFM 2020; CSO, 2022
Clover	Based on cost of seed and reseeding by agricultural contractor. Contractor rates of €116.14 ha^{-1} for reseeding of grassland with clover and €10 kg^{-1} of seed at a rate of 5kg ha^{-1}.	FCI, 2020; Humphreys, 2020.
Liming	Based on €25 tonne^{-1} ha^{-1} of lime applied to area spread by agricultural contractor. An additional cost included is for periodic soil sampling and analysis at €24 sample^{-1}. Cost accounts for reduced fertiliser use due to increased NUE.	Teagasc, 2020; FCI, 2020
Low emission slurry spreading – LESS	Based on contractor cost of slurry spreading of €65 h^{-1} for splashplate and €85 h^{-1} for LESS and working rate of three tankers h^{-1} for splashplate and 2.5 tankers h^{-1} for LESS. Cost savings are also included for reduced fertiliser use due to increased NUE.	FCI, 2020; Burchill, 2019; DAFM,2020
Covering slurry stores	€1.5 m^{-3} of slurry based on installation of a flexible floating cover. Cost also accounts for reduced fertiliser use due to increased NUE.	Reis et al., 2015; CSO, 2022
Reducing crude protein content of diet	€6 tonne^{-1} reduction in the price of dairy concentrates, based on the market price differential between protein ingredients.	Patton, 2020
Slurry amendments	Based on the cost of treatment of €2.34 m^{-3} for dairy slurry and €4.40 m^{-3} for cattle slurry, due to differing slurry dry matters. Cost savings are also included for reduced fertiliser use due to increased NUE.	Kavanagh et al., 2019; CSO, 2022
Low emission slurry spreading – LESS	Based on contractor cost of slurry spreading of €65 h^{-1} for splashplate and €85 h^{-1} for LESS and working rate of three tankers h^{-1} for splashplate and 2.5 tankers h^{-1} for LESS. Cost savings are also included for reduced fertiliser use due to increased NUE.	FCI, 2020; Burchill, 2019; DAFM, 2020 CSO, 2022
Reducing crude protein content of diet	1, 2 and 2 percentage points 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
Covering slurry stores	€4 m^{-3} for the installation cost of rigid covers on pig slurry stores. Cost savings are also included for reduced fertiliser use due to increased NUE.	Reis et al., 2015; CSO, 2022
Slurry amendments	Based on the cost of treatment of €2.34 m^{-3} for dairy slurry due to similarity in dry matter content. Cost savings are also included for reduced fertiliser use due to increased NUE.	Kavanagh et al., 2019; CSO, 2022
Drying of poultry manure	Based on cost of €28 100 bird places^{-1}.	Reis et al., 2015.
Poultry manure amendments	Cost of €18.72 m^{-3} of manure due to adjustment to high dry matter of 30%. Cost savings are also included for reduced fertiliser use due to increased NUE.	Kavanagh et al., 2019; CSO, 2022