Analysis of Marginal Abatement Cost Curve for Ammonia Emissions: Addressing Farm-System Heterogeneity.

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Abstract

There exist an urgent need to reduce ammonia (NH_3) emissions to control air pollution and moderate other related environmental and health hazards. . This study adopts farm-level marginal abatement cost curve (MACC) analysis across different farm typologies in Ireland. The study also addresses the interactions amongst the abatement options and the presence of farm heterogeneity in order to examine whether it is sub-optimal to adopt a single marginal abatement cost curve across different farm systems. Teagasc National Farm Survey (NFS) 2020 data was used as the basis of the analysis in the paper. The findings show that the selected measures are effective in abating ammonia emissions at varying levels across the different farm typologies. Liming, protected urea and crude protein in diets were primarily cost-saving while the clover measure examined moved between cost-saving and cost positive across the different farm types. The presence of heterogeneity across the farm typologies was further supported by the difference in the MACC diagram of the farm types. Furthermore, a higher abatement potential (>100 kgNH3) was reported for the combined measure as against the stand-alone measures.

Keywords: Farm-level, MACC, ammonia, environment, mitigation, interactions

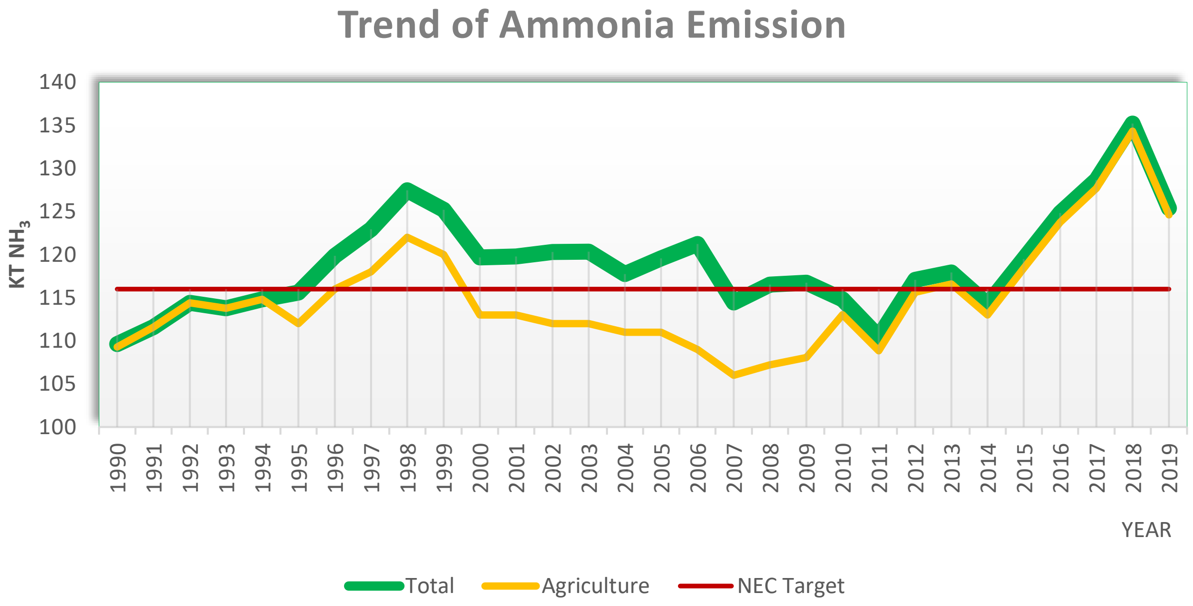
JEL Code: Q53 Air Pollution; Water Pollution; Noise; Hazardous Waste; Solid Waste; Recycling

1. Introduction

Sustainable food production encompasses the "shared responsibility for the production, supply, and consumption of safe and nutritious food while simultaneously protecting the natural environment and quality of life now and into the future" (Bord Bia, 2020). The quest to achieve sustainable food production is the central aim of many national and global communities. However improving food production to attain food security and providing an acceptable welfare status for farmers often comes at the detriment of the environment as agricultural activities may lead to environmental degradations (Buckley & Donnellan, 2020). Actions are therefore required to minimize the negative environmental influences ,such as greenhouse gas and ammonia emissions, water pollution, and biodiversity losses associated with agricultural production.

Agriculture is an important source of gaseous emissions accounting for approximately 85% of all ammonia emissions globally (Bouwman et al., 1997; Zhang et al., 2011; Xu et al., 2018). Agricultural ammonia emissions in Ireland are reflected in their total ammonia emissions (shown in Fig. 1) , since 99.4% of ammonia emissions in the country is accounted for by Irish Agriculture (Hyde et al., 2021). This is similar to German agriculture which accounts for 95% of their total national ammonia emissions (Wagner et al., 2017). The European Environment Agency EEA (2019a) has indicated that the poor air quality associated with ammonia emissions in Ireland could lead to over 1000 premature deaths. Other negative consequences of ammonia emissions include destruction of the aquatic, plant and forest systems through increased acidity of water bodies (EEA, 2019b).

The EU National Emissions Ceilings (NEC) Directive sets limits for ammonia emissions at the member state level. Ireland was initially allocated a fixed annual emissions ceiling of 116 kilotonnes of ammonia NH_3 (NEC Directive 2001/81/EC) which continued to apply until the 31st of December 2019. Beginning in 2020, Article 4(1) of Directive 2016/2284 set down new national emission reduction ceilings for each EU Member State for the years 2020 to 2029 and 2030 onwards. These new targets have to be achieved relative to the levels of emissions in the base year of 2005. For Ireland, these reduction commitments currently equate to a limit of 112.13 kT NH_3 to be achieved in the 2020 commitment period and a 107.5 kT NH_3 to be achieved in the 2030 commitment period.thus there is an urgent need to optimize the reduction of ammonia emissions at the farm level.   Figure 1 below shows the trends in national ammonia emissions to 2019. According to the EPA (2021), Ireland has failed to achieve its NEC Directive target for ammonia in 7 of the last 9 years.



Source: EPA Ireland's Air Pollutant Emissions 1990-2030 report (EPA, 2020, 2021), EPA Ireland's Informative Inventory Report 2021(Hyde et al., 2021) and Central Statistics Office Environmental Indicators Ireland 2021 Data (CSO, 2021).

Figure 1: Trend of ammonia emissions.

Many studies (MacLeod et al., 2010; Moran et al., 2011; Bockel et al., 2012; Hou et al., 2019) have adopted the use of the MACC to study the abatement of gaseous emissions. However, the focus has principally been on greenhouse gases and not ammonia. In Ireland, a few studies (Lanigan et al., 2015; Buckley et al.,

2020) investigated the abatement of ammonia emissions using the MACC methodology but these studies were at the aggregate scale and may not provide a nuanced understanding of marginal costs for particular farms/farm types. Other studies such as (Holly et al., 2017; Wang et al., 2017) assessed the farm-level abatement of NH_3 emissions in the USA and China but focused only on dairy and swine farms, respectively. However this work has not been carried out for Ireland, finding from the USA and China are not likely to translate here due to different biophysical environments and regional policies.

This paper hypothesizes that ammonia mitigation measures will impact farm types differently and public policy dictates that any measures that are promoted must be cost-effective. Policies that fail to recognise heterogeneity are unlikely to lead to efficient ammonia mitigation. Therefore, this research assesses the cost-effectiveness of potential ammonia mitigation measures across all of the dominant system types in Irish farming. In this context, this paper seeks to address the following research questions: (1) Is the ranking of mitigation measures consistent across farm system types? (2) Is the cost-effectiveness of mitigation measures significantly different across different farm system types? and (3) Are the abatement potentials of the individual (standalone) measures significantly different from the combined measures? Thus, this article proceeds in the following manner section 2 critically reviews the literature on ammonia emission. Section 3 deals with the methodology, Section 4 focuses on results and discussion and Section 5 concludes.

2. Background and Theoretical Framework

The crucial need to investigate the relationship between energy-saving and the associated cost during the oil crisis in the 1970s gave rise to the origin of the MACC (Huang et al., 2016; Eory et al., 2018). The MACC previously known as supply curves were initially developed and applied by Meier et al. (1982) to evaluate the cost-effectiveness of residential energy conservation measures (Kesicki & Strachan, 2011; Wächter, 2013; Levihn, 2015; Eory et al., 2018). The MACC was subsequently adopted to identify cost-effective abatement measures for air and water pollution (Silverman, 1985; Braden et al., 1989; Cowell & Apsimon, 1998; Lanigan et al., 2015)

In the 1990s, the MACC concept was further extended to assess the issues of global climate change (Jackson, 1991). The full enforcement of the United Nations Framework Convention on Climate Change (UNFCCC) came into being in 1994, it seeks collaborative efforts amongst most nations of the world to take up the duty of reducing greenhouse gas emissions (Huang et al., 2016).

The hypothesis behind this study is that both environmental and farm-level economic models can be combined to generate a cost-effectiveness estimate of potential abatement options for ammonia emissions across the different farm systems. The marginal abatement cost curve methodology is a technique to assess the abatement potential of different abatement options and the relative cost associated with each measure. It can potentially suggest an economically optimal mitigation level (Bockel et al., 2012). Another function of the MACC is to rank abatement options from those measures that are cost-beneficial (i.e., measures that not only reduce gaseous emissions but also save money) to those that are cost-prohibitive (i.e., measures that save gaseous emissions but are too costly or more expensive than the price of gaseous emissions). It visualizes the magnitude of the abatement potential of each measure, as indicated by the width of the histogram with the height representing the height of the histogram (Schulte & Donnellan, 2012; Lanigan et al., 2018).

Relatively few studies have focussed on the abatement of NH_3 in comparison to that of GHG. A number of studies used the MACC methodology to examine the abatement of GHG emissions in the UK. For example, MacLeod et al. (2010) used a top-down approach to MACC analysis which revealed the effect of interaction among mitigation measures on cost-effectiveness and total abatement potential. The results of stand-alone and combined mitigation measures were compared and revealed large discrepancies between some stand-alone and combined measures, which emphasized the importance of accounting for interactions when constructing MACCs. The authors recommended the need to take into account the dynamics in the cost-effectiveness of abatement measures.

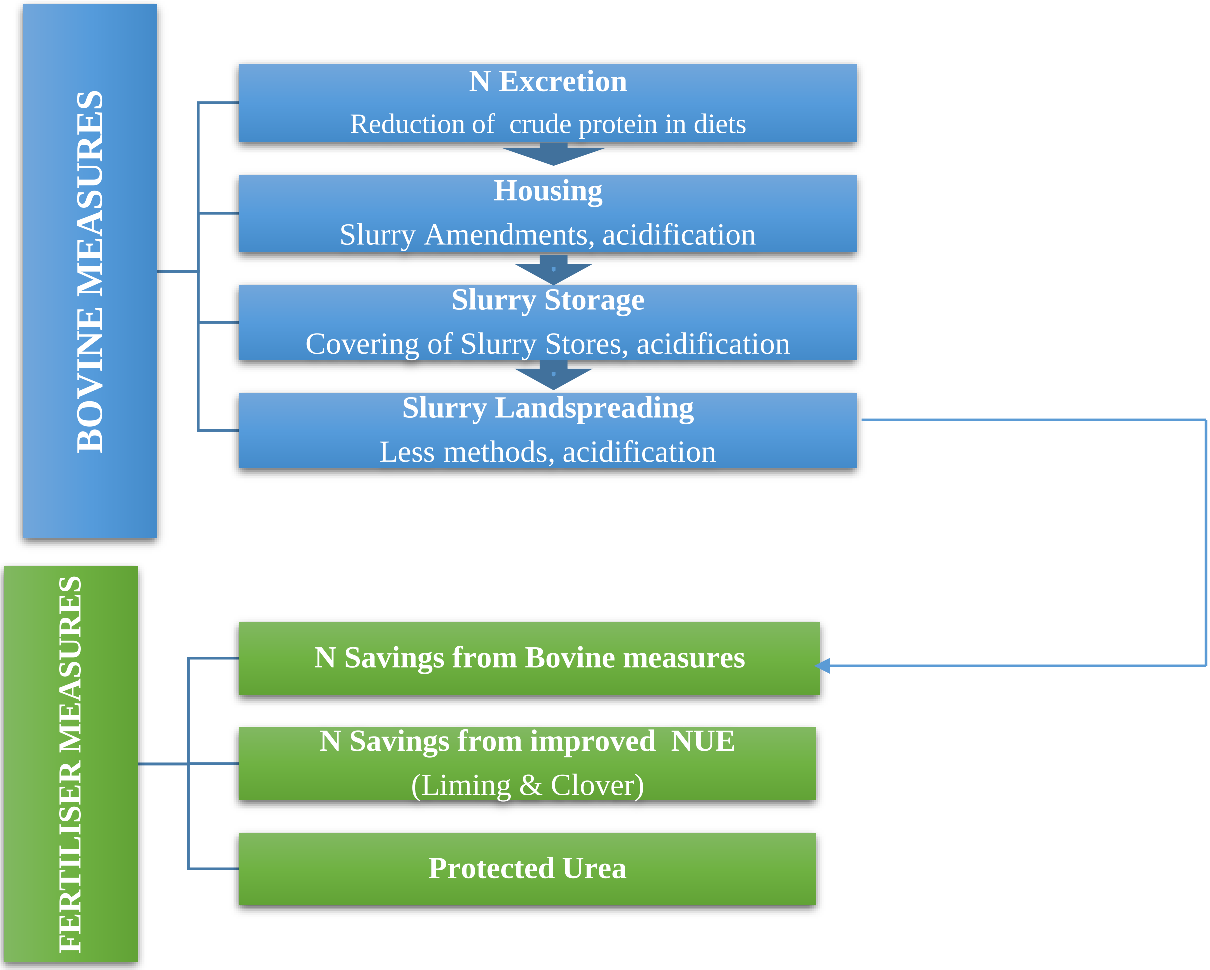
Jones et al. (2015) developed a farm-specific GHG MACC framework for sheep farming systems in the UK using six abatement measures across three different farm typologies. Their report revealed variations in the three different MACCs for the farm categories with the ranking of the abatement measures fluctuating from cost-negative to cost positive; thus supporting the presence and the need to account for heterogeneity in MACC analysis. Wagner et al. (2017) conducted a similar study in the north-western German Federal State of Lower Saxony, Germany. They assessed the implication of NH3 abatement measures on farmers' costs and society's benefits. Common abatement measures studied in the research included low emission slurry spreading (LESS) and the covering of slurry stores and concluded that research on NH3 abatement should be carried out for different farm types. Zhang et al., (2020) assessed China's marginal abatement cost curve of agricultural ammonia emissions for different farm systems at the aggregate level. Cost-effective measures in the study included reduction in synthetic nitrogen fertiliser and lowering nitrogen-feeding options.

In the Republic of Ireland, Lanigan et al. (2015) used the MACC methodology to evaluate the abatement potential and the associated cost of some mitigation measures including change of chemical fertiliser formulation, the addition of chemical amendments to animal manure and the use of low emissions slurry spreading equipment. Buckley et al. (2020) built on and updated the work of Lanigan et al. (2015). However, these studies were conducted at the national aggregate scale and assumed a one-fit-all approach to the evaluation of ammonia mitigation measures.

2.1 Nitrogen Flow Framework

Following the Nitrogen flow model proposed in the EMEP/EEA Emission Inventory (Zhongming et al., 2019), Figure 2 illustrates where ammonia emissions occur at different stages of the agricultural system. In this study, these stages are broadly classified as the manure management chain and the fertiliser application as illustrated in Fig.2.

At the manure management stage, ammonia is emitted through nitrogen excretion in diets, housing, slurry storage and slurry spreading. Abatement measures thus work by reducing ammonia emissions at a specific stage of the nitrogen flow. The implementation of abatement measures can occur either at a stage on the production chain, for instance, the reduction of crude protein in the diets of dairy cows is applied during feed intake to reduce the nitrogen excreted by livestock. In this case, the abatement measure is classified as an individual abatement measure applied hitherto referred to as a "standalone measure". Also, reduction of ammonia emissions can occur at more than one stage of the manure management chain and/or the fertiliser point simultaneously, this is referred to as combined measure. It is noteworthy that the implementations of the abatement strategies at the different stages are interdependent and are not additive (Webb et al., 2005). Webb et al., (2005) emphasised the importance of reducing ammonia emissions at each stage of the manure management, mainly due to the loss of ammonia emissions at the housing, storage and spreading stages of the manure management chain. In addition, abatement of NH_3 emissions along the manure management chain is further reduced because of increased nutrient use efficiency of organic manures from the manure management chain thus reducing the need for chemical fertiliser application.



Source: Adapted from Buckley et al. (2020)

Fig. 2 Framework of Nitrogen Flow Adopted in the MACC Analysis.

The N_2 in manure can be converted to NH_3 through bacterial degradation, primarily urease, an enzyme produced by microorganisms in feaces, reacts with urinary urea to form NH_3 (Ishler., 2016).

3. Methodology

Following the EPA 2020 methodology (Duffy et al., 2020), the total farm ammonia emissions across different farm activities are calculated as a product of the activity data and a set of emission factors for the particular source (e.g. housing, storage or land spreading for manure management, inorganic nitrogen fertilizers) .

$$Total\ NH_3 = Activity\ data * Emission\ factor \quad (1)$$

While the data on emission factors were obtained from the Irish National Inventory Report (EPA, 2020), the activity data were obtained from the Teagasc (Irish Agricultural and Food Development Authority) National Farm Survey (NFS) 2020 dataset which is part of the European Union Farm Accountancy Data Network (FADN). The EU FADN obtains data relating to business and farm incomes of agricultural enterprises from farms across the EU, which involves sampling about 80,000 farm holdings, out of a population of approximately 5 million farms across the EU. Physical (e.g.

location) and structural (e.g. livestock numbers) data are also collected which are increasingly used to create sustainability indicators (Hennessy et al., 2013). The data collected in the FADN sample reflects about 90% of the total cultivated agricultural area and total agricultural production of the EU. The Teagasc NFS data are nationally representative and generally report results across five farm systems; specialist dairy, cattle production, specialist sheep, specialist tillage and mixed livestock systems.

For a detailed explanation of the different farm types, see Table 1. Farms are selected into the sample to be representative of farms across the population based on population weights provided by the Central Statistics Office of Ireland. Activity data is collected on NFS farms across a range of areas including animal inventories, land and cropping area, manure management practices, chemical fertilisation practices and technology adoption. Table 2 provides summary statistics for farms within the sample. It shows that the farm size of the cattle and sheep farms are comparatively low relative to the other farm types. The farms are categorized based on the main or dominant enterprise practised and need not exclusively be the only activity being carried out on the farm (Buckley et al., 2015).

Table 1 Description of Farm Typologies

Farm Type	Description
Specialist Dairying	Dominant enterprise is specialist milk production
Cattle	Involves both Cattle Rearing and Cattle Other. Cattle Rearing−≥ 50 % of the standard output of rearing and fattening is from suckler cows. Cattle Other- <50% % of the standard output of rearing and fattening is from suckler cows.
Sheep	Dominant enterprise is sheep; either specialist sheep or sheep and cattle combined),
Tillage	Dominant enterprise is cereals or root crops)
Mixed Livestock	Some combination of grazing livestock (dairy, cattle, sheep) or grazing livestock combined with a crop enterprise; Dairying tends to be the main livestock enterprise.

Source: Buckley et al. (2015).

Table 2 Farms Profile from NFS 2020 Data

Parameters	**Farm Types**					
	Specialist Dairy	Cattle	Specialist sheep	Tillage	Mixed Livestock	Total
Farm size (ha^{-1})	60.76	33.94	44.30	61.17	64.35	42.61
Livestock Units (ha^{-1})	139.43	53.98	68.53	41.35	159.75	86.20
Sample size	274	341	108	59	13	795
Sample size (Weighted to population)	15204	54020	14322	6879	1840	92264

A detailed explanation of the different farm categories is given in Table 2.

3.1 *Marginal Abatement Cost Curve (MACC)*

Expert-Based Method: This is also referred to as the financial accounting approach. It involves estimating a net present value (NPV) to determine the “incremental cost” of the alternative abatement measures relative to the business as usual (BAU) scenario (baseline scenario), which is then divided by the emission reduction obtained by implementing the alternative measure (Moran et al., 2011; Schwarz et al., 2013; Dequiedt & Moran, 2015; Lanigan et al., 2015; Lanigan et al., 2018).

The cost-effectiveness is calculated by the ratio of the Net Present Value and the discounted lifetime abatement given as (Eory et al., 2015):

$$MAC = \frac{NPV}{kgNH_3\ avoided} * -1 \qquad (1)$$

Where

NPV= Net Present Value this is the discounted stream of net costs that accrue after the intervention.

$kgNH_3\ avoided = (kilogram\ of\ ammonia\ emissions\ avoided)$

3.1.1 *Selection of Abatement Measures*

The selection of abatement options was based on past literature (O'Brien et al., 2014) relevant to conditions in the Republic of Ireland as the implementation of abatement measures is mainly dependent on the socio-demographic characteristics (Ogunpaimo et al., 2021) and biophysical environment in which the farms and/or farmers are located. The study selected mitigation measures follow the work of Lanigan et al. (2018) and Buckley et al. (2020). The justification for using these measures is that these options had been deemed applicability to Irish agriculture all be it at an aggregate scale. These studies also suggested adoption rates for mitigation measures. Secondly, the availability of data on associated cost and benefit of individual measures along with their volume of abatements. Following Lanigan et al., (2015) and Buckley et al. (2020) the abatement measures related to NH_3 emissions for this study include:

1. Use of Protected Urea chemical N fertiliser formulation
2. Achieving optional soil pH through liming
3. Introduction of clover into grass swards
4. Use of low emissions slurry spreading (LESS) equipment
5. Addition of chemical amendments to bovine manure at the storage
6. Reduction in the crude protein of dairy cow concentrates
7. Covering of manure slurry stores

It is noteworthy that there are other NH_3 abatement measures applicable to Irish agriculture and studied by Lanigan et al. (2015) and Buckley et al., (2020) but not considered in this study as they were deemed to lie outside the scope of the farm system level examination employed here[1]. The seven strategies considered in this study are those that mitigate NH_3 emissions and all are applicable to land-based farm systems in Ireland.

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[1] Lanigan et al., (2015) and Buckley et al., (2020) considered the pigs and poultry farms in their report.

Table 3: Assumptions Applied to Modelling Mitigation

Abatement Measure	**Intervention**	**Abatement potential Assumptions**	**Cost Assumptions**	**References**
PROTECTED UREA	Switch from straight urea to protected urea	it was assumed that all straight urea used on farms was replaced fully by protected urea.	Cost per kg of Straight urea- € 0.73, CAN fertilizer-€ 0.87 (Irish Central Statistics Office (2021)).	C. S. O. CSO (2021) Buckley et al. (2020)
		Emission factors of straight urea is 155 (NH3 - g per kg) compared to 33 NH3 - g per kg for protected urea (EPA, national inventory)	The price of protected urea was assumed as an average of the price of the CAN fertiliser and straight urea	Buckley et al. (2020)
LIMING	The application of lime on farms'acidic soils to increase soil pH and plants performance.	This research assumes that **ALL** sub-optimal soils are treated with lime.	In line with recommended guidelines (Teagasc, 2020) a soil sample is assumed to be taken for every 3 hectares of land targeted under this pathway at a cost of €25 per sample to be tested in the laboratory.	Teagasc (2019) Teagasc (2020)
	Based on Teagasc 2019 soil analysis status and trends test only 54% of dairy farms,50% of cattle and sheep farms and 78% of tillage farms have optimum soil ph (>6.2).	Based on Teagasc long-term soil experiments the pH response rate is 1 t/ha =0.15 pH units for mineral soils (i.e soil pH<5.5) and 1 t/ha =0.2 pH units for soils with pH between 5.5-6.2.	Following Buckley et al. (2020) the cost of lime, including the cost of application to the field, is assumed to be €25 per tonne.	Buckley et al. (2020)
	22%, 19% and 5% of dairy farms have a soil pH of 5.9-6.2, 5.5-5.9 and <5.5 respectively.	The soil pH and the pH response rate were used to estimate the quantity of lime required for each category of soil sub-optimality and across different farm types.	As against Lanigan et al., (2018) and Buckley et al., (2020) which assumed a dynamic abatement of gaseous emissions and cost of abatement, this research assumes a one-off implementation of abatement measures thus the cost of liming and sampling were discounted at a rate of 20% for 5 years.	
	1%, 9% and 12% of tillage farms have a soil pH of 5.9-6.2, 5.5-5.9 and <5.5 respectively.	80kg of N/ha was released from liming thus reducing the need for chemical fertilizer application.	The number of years used in discounting the amount of liming was based on Teagasc (2021) advice on liming which stated that a replacement of lime is required approximately every 5 years	Teagasc (2021)
	8%, 21% and 21% of cattle and sheep farms have a soilpH of 5.9-6.2, 5.5-5.9 and <5.5 respectively.			

Table 3: Assumptions Applied to Modelling Mitigation

Abatement Measure	Intervention	Abatement potential Assumptions	Cost Assumptions	References
CLOVER	The importance of using clover as an abatement practice can be attributed to its natural fixation of nitrogen which reduces the need for chemical fertilization, thus reducing emissions from chemical fertilizer application	The study assumes that ALL grassland area is reseeded with clover.	€116.14/ha was assumed as the contractor rates for reseeding of grassland with clover.	(FCI, 2020). Buckley et al. (2020)
		The nitrogen fixation of clover was fixed to a maximum of 80 kg N ha-1 yr-1.	The cost of clover seed is €50 per hectare (Buckley et al., 2020) .	Buckley et al. (2020) Lanigan et al. (2018)
		All chemical N savings are captured through reduced protected urea fertiliser applications.	Similar to liming the cost of reseeding clover were discounted at a rate of 20% for 5 years (Teagasc, 2017).	Buckley et al. (2020) Teagasc (2017)
BOVINE MEASURES				
LESS	Splashplate method which is the most popular method broadcasts the slurry over a wide area.	The new scenario was developed based on the assumption that 100% of slurry applied by splashplate in the base year was substituted to LESS, which a 50/50 split between trailing shoe and trial hose methods.	Cost were estimated based on relative contractor rates for application which suggests that using a 11500-litre tanker, the cost of slurry spreading by splash plate and LESS method is €65/hour and €85/hour respectively	Buckley et al. (2020) Lanigan et al. (2018)
	Alternative application methods exist under the broad label of Low Emission Slurry Spreading techniques (LESS). LESS consists of the use of slurry injection, trailing hose and trailing shoe, which reduces ammonia emissions in place of splash plates.	The use of trailing hose results in a 30% reduction of NH3 emissions as against splash plate (Bittman et al., 2014; Buckley et al., 2020).	The volume of slurry spread by LESS and splash plate per hour for an 11,500-litre tanker is assumed to be 28.4m^3 and 34 m^3 respectively.	Bittman et al. (2014)
	LESS is based on the principle of reducing the area of the ammonia emitting surface, in this case of 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	The use of trailing shoe results in a 60% reduction of NH3 emissions as against splash plate (Bittman et al., 2014; Buckley et al., 2020)		
		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.		

Table 3: Assumptions Applied to Modelling Mitigation

Abatement Measure	**Intervention**	**Abatement potential Assumptions**	**Cost Assumptions**	**References**
Slurry Ammendments	The emissions of NH3 during the slurry storage stage can be offset by the inclusion of chemical amendments (Kavanagh et al., 2019). These amendments may include such chemical as alum, ferric acid, sulphuric acid and acidic acids	This mitigation scenario is based on the assumption that compound alum is the treatment added to the bovine slurry and that this reduces NH3 emissions at the slurry storage stage by 70% with a 100% adoption rate assumed among farmers.	The treatment cost per volume of slurry treated is assumed to be €2.34 per m^3 and €4.40 per m^3 for dairy and cattle slurry respectively (Kavanagh et al., 2019) .	Buckley et al. (2020) Kavanagh et al. (2019)
		The adoption rate is assumed to be 100%	The extra N retained over the baseline level represents a benefit and is accounted for as the cost of protected urea fertiliser	Buckley et al. (2020) Lanigan et al. (2018)
		The adoption of the slurry amendment leads to a reduced requirement for chemical fertilizer due to the increased quantity of nitrogen captured in the slurry and later returned to the soil at the land spreading stage of the manure management chain.	.	Buckley et al. (2020) Lanigan et al. (2018) Teagasc (2017)
Covering of Slurry Stores	NH3 reduction at the slurry storage stage leads to higher nitrogen retention for use within the farm system. This in turn reduces the requirement for chemical nitrogen fertiliser for a given level of agricultural production. All cover types were posited to reduce NH3 emissions (Kupper et al., 2020)	The assumptions behind the adoption of the covering of slurry stores are based on the use of a flexible floating cover and an implementation rate of 100% (that is, it involves moving all uncovered stores to covered stores).	On the cost side, the assumption was based on the report of Reis et al. (2015) which assumes a cost of €1.5 per m3 of slurry to replace an open slurry store with a covered slurry type.	Buckley et al. (2020) Reis et al. (2015)
		The emissions factors for covered stores is 50% lower than for uncovered slurry stores. (Misselbrook et al., 2016.)	The total cost of replacing an open slurry to a covered type was discounted over a period of 10 years	Misselbrook et al. (2016.)
		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 (Wall, 2020a).		
Crude Protein	Excess crude protein (over requirement) in the diet of bovines and pigs leads to higher N excreation rates and ultimately higher ammonia emissions (Sajeev et al., 2018; Buckley et al., 2020)	It is assumed that the average dairy cow was fed 1,045 kg of concentrates (Buckley et al., 2020). Furthermore, it is assumed that a 1% decrease in the crude protein composition of dairy concentrates leads to a decrease of 1.5 kg in the N excretion rate of dairy	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 (Buckley et al., 2020).	Shalloo et al. (2018); (O'Brien et al., 2018)
	This abatement measure works by influencing the amount of nitrogen excreted by livestock and by extension those entering the manure management chain (Buckley et al., 2020).			O'Brien and Shalloo (2019).

4. Results

The results of farm-level abatement, cost of abatement and cost-effectiveness are presented in this section. As indicated, seven categories of abatement measures were considered in this study for five different farm types. The current ammonia emissions scenario is treated as the business as usual scenario for all the abatement measures assessed in this study, for the description of the baseline emissions across the different farm systems is shown in Table 4 (for further details see appendix).

4.1 Farm-level Baseline Emissions

Table 4 describes the baseline ammonia emissions across the different farm systems. It is noteworthy that some abatement measures such as LESS are already adopted by some farms in the baseline period as as shown in Table 4

Table 4 Description of the Baseline Emissions

	Specialist Dairy	**Cattle**	**Specialist sheep**	**Specialist Tillage**	**Mixed Livestock**	**All farms**
Baseline Emissions (kg NH3) per farm	2866.80	744.12	524.61	595.48	1802.37	1069.84
Baseline Adoption of Abatement Measures						
1. Protected Urea	16.31%	2.53%	8.45%	1.98%	3.12%	5.69%
2. Liming	54%	50%	50%	78%	66%	53%
3. Clover	174.47	28.71	33.08	10.74	81.23	53.11
4. Low emissions slurry spreading (LESS)	49.92%	15.16%	8.85%	17.45%	25.19%	20.28%
5. Slurry amendments	0%	0%	0%	0%	0%	0%
6. Reduction in crude protein - dairy cows	0%	0%	0%	0%	0%	0%
7. Covering of slurry stores	84.62%	92.94%	94.94%	91.16%	98.39%	91.85%
* Combined Measure	743.54	150.22	110.44	101.06	410.30	243.34

4.2. Farm-Level NH_3 Abatement Potentials

For a typical Irish farm in the NFS, as reported in Table 5, the standalone results of the individual strategies, the LESS measure accounted for the main (33%) of NH3 emissions (92.19 kgNH3) abated. This implies that an average Irish farm will abate 92.19 kg of NH3 emissions if they implement the use of LESS measure as against the use of splash plate.

The use of protected urea recorded the second-highest level of abatement potentials (62.28 kg NH3); this is followed by the adoption of clover. It can be interpreted that the use of clover as an abatement measure will reduce 53.11kg of NH3 emissions, the reduction in crude protein and covering of slurry stores measures accounted for the lowest levels of NH3 emissions abatement compared to other measures considered in this study.

Contrary to the results of the other farm categories, the LESS measure did not account for the highest abatement potential for the specialist dairy and tillage farms, mainly because in the case of the specialist dairy farm, more of the farms in the NFS (~50%) has resulted to the adoption of LESS measure by the year 2020. It can be interpreted that 183.74 kg of NH3 emission is reduced by a dairy farm that adopts the use of LESS measures as against the baseline scenario of using a splash plate. It is indicative that mixed livestock farms have the highest abatement potentials for the LESS option with a reduction of 196.28 kg of NH3 reduced. The average cattle and sheep record abatement potentials of 83.21 kg NH3 and 49.52 kg NH3 respectively when implementing the LESS measures.

Replacing all the grassland area of an average Irish dairy farm with clover results in 174.47 kg of NH_3 abatement while applying all sub-optimal soils within a dairy farm with lime leads to an abatement of 86.39 kg of NH_3. Other abatement measures such as slurry amendment, crude protein in diets and covering of slurry stores led to 109.06 kg NH3, 30.06 kg NH3 and 28.6 kg NH_3 reductions respectively.

Dairy had the highest level of abatement potential across all the measures; generally between 5-7 times higher than for the cattle and sheep systems, 9 times higher than tillage and double that of mixed livestock. LESS delivered the highest level of NH_3 mitigation across all farm enterprises except for dairy and tillage where protected urea was highest. The use of protected urea results in a high net reduction of NH_3 emissions of 287.07 kg of NH3 (32.9% of the total average abatement potential) for an Irish dairy farm. The abatement potentials reported for all farms is significantly lower than that of dairy and mixed livestock farms and higher than the other farm categories for all the abatement measures. Typically the abatement potential of the dairy farm is about 2 times that of the All farm for LESS measure to quintuple for the protected urea and covered measures.

The result of the combined measure, that is, the interaction of all the individual measures leads to a higher abatement potential across the different farm types. The overall impact of interacting the abatement measures results in a synergistic relationship among the measures. The abatement potential for the combined measure ranges from 101.06 kg NH_3 for the tillage farm to 743.54 kg NH_3 for the specialist dairy farm. The combined abatement potential for the dairy farm is about seven times that of the tillage farm. These interactions, however, are not additive in nature.

Table 5 Farm-level NH_3 Abatement Potentials

Abatement potential (kg NH3) per farm	**Specialist Dairy**	**Cattle**	**Specialist sheep**	**Specialist Tillage**	**Mixed Livestock**	**All farms**
1. Protected Urea	287.07	13.94	20.30	32.15	63.60	62.28
2. Liming	86.39	16.69	20.55	14.84	31.77	28.94
3. Clover	174.47	28.71	33.08	10.74	81.23	53.11
4. Low emissions slurry spreading (LESS)	183.74	83.21	49.52	21.41	196.28	92.19
5. Slurry amendments – Bovine	91.33	16.92	8.87	9.52	51.78	28.08
6. Reduction in crude protein - dairy cows	33.06	9.66	5.31	6.60	22.22	12.86
7. Covering of slurry stores	16.48	0.89	0.09	0.12	3.77	3.33
Total	**872.54**	**170.02**	**137.72**	**95.38**	**450.65**	**280.79**
* Combined Measure	743.54	150.22	110.44	101.06	410.30	243.34

Source: Authors Computation of 2020 NFS and NIR data

4.3 Cost of Farm-level Abatement

Despite the merits of the mitigation measures, the cost of adopting a measure needs to be considered since the primary aim of farming, like any other business, is to maximize profit. This section presents and discusses the cost implications attached to the seven abatement measures across the five farm systems. These are calculated as the difference in the new cost of implementation of the abatement measures and the baseline cost less any accrued financial benefits (e.g. reduced chemical N fertilizer use) associated with the expressed in monetary terms. A negative value (-) in Table 6 represents a benefit (cost-saving) and (+) sign actual cost.

From the results obtained (Table 6), there are monetary benefits associated with implementing the fertilizers measures across the five categories of farms. Amongst the fertilizer measures, the liming option incurred the highest benefit (€558.35), followed by clover (€290.71) then crude protein (€206.82) across all farm systems. Considering the heterogeneity across the farm types, disparities exist in the values of each measure’s benefit. From Table 6, it is fallacious to interpret liming as the cheapest measure as reported by the result of the all farm; it is more expensive than clover for the dairy farm.

Therefore, the results further justify the need to consider farms heterogeneity and also the biophysical environment in constructing MACC curves.

Overall, the cumulative cost implication of abatement measure for the dairy farm is cost-saving and largely influences the cost-behaviour for all farms combined. For instance, where an abatement measure (LESS) is cost-positive for the dairy farm, it is also cost positive for all farm and where it is cost-saving for the dairy farm, it is also cost-saving for all farm. The cost of abatement for the dairy farm is about fourteen times cheaper than the all farm, eleven times cheaper than the mixed livestock

For an Irish dairy farm, the clover measure is the cheapest measure with a saving of about €1549.67, while the mixed livestock and the cattle farms also incurred a benefit in the implementation of the clover option. The average Irish tillage and sheep farm on the other hand incur a cost of €165.73 and €137.22 respectively. For all other farm types except the dairy farm, the liming measure is the cheapest abatement option.

The bovine measures are more expensive to use (except for the reduction in crude protein). Unlike the fertilizer strategies, farmers will incur some level of cost should they adopt the bovine measures. The slurry amendment option is the most expensive strategy to use amongst the bovine measures and by extension across all measures. It costs an average Irish farmer €812.72 to adopt the use of slurry amendments and specifically €1409.84 for an average Irish dairy farmer.

Combining abatement options also has its monetary implications. A monetary benefit may be in the form of benefit attached to the amount of fertiliser saved. Interaction of all measures accumulates benefits across the farm types considered in this study. The benefit ranges from approximately €758.12 for an average cattle farm to €6254.86 for an average dairy farm.

Table 6 Cost of Abatement Measures Per Farm

Cost per farm (€)	**Specialist Dairy (N=15204, 60.76 ha^{-1})**	**Cattle (N=54020, 33.94 ha^{-1})**	**Specialist sheep (N=14322, 44.30 ha^{-1})**	**Specialist Tillage (N=6879, 61.17 ha^{-1})**	**Mixed Livestock (N=1840, 64.35 ha^{-1})**	**Total (N=92264, 42.61 ha^{-1})**
1. Protected Urea	-23.77	-1.15	-1.68	-2.66	-5.27	-5.16
2. Liming	-1336.97	-398.61	-337.49	-517.36	-686.66	-558.35
3. Clover	-1549.67	-102.00	137.22	165.73	-465.98	-290.71
4.Low emissions slurry spreading (LESS)	126.92	102.18	67.64	33.29	202.47	97.76
5. Slurry amendments – Bovine	1409.84	767.08	460.17	394.45	1526.55	812.72
6. Reduction in crude protein	-745.16	-105.76	-59.93	-68.23	-385.96	-206.80
7. Covering of slurry stores	7.89	0.82	0.06	-0.04	2.20	1.83
* Combined Measures	-6254.86	-758.12	-1074.33	-1955.66	-2632.86	-1839.64

Source: Authors Computation of 2020 NFS and NIR data

4.3 Farm-level Marginal Abatement Cost Curve

Assessing the efficacy of abatement measures requires considering both the abatement potential and the cost of abatement of each measure. The marginal abatement cost of ammonia emissions (expressed as €

per kg of NH_3 abated) can be compared across different farm typologies and measures can be ranked in terms of their cost-effectiveness.

As explained in the previous sections, a negative (-) implies a measure that reduces ammonia emissions and also saves money to the farmer, while a positive (+) sign indicates that although the measure reduces ammonia emissions, there are associated costs to the implementation of the measures by the farmer. Explaining the individual measures MAC for a typical average (ALL) farm shown in Table 7, the cost-beneficial measures (see Fig. 3) are liming, crude protein, clover and protected urea with liming considered the most cost-beneficial measure with a marginal abatement cost of -€27.35, followed by the crude protein reduction in diets (-€11.85) and clover (-€2.40). Other measures are considered cost-positive measures, from the covered stores (€0.03) to the slurry amendments (€34.85).

The MACC diagrams for all farm types are illustrated in Figures. 3a-3f. They are the representation of the individual abatement measures from the most cost-beneficial measures to the most cost positive measures. The cost-effectiveness of the abatement measures for farm typologies are also presented in Table 7. As presented the behaviour of the abatement measures varies across the farm types, for instance, while the clover is cost negative for dairy, it is cost positive for some other farm types like sheep and tillage. These variations in the MACC diagram and rank of abatement options may be attributed to the presence of heterogeneity across the farm types. As shown in Fig. 3-8 no two farm types have the same MACC. Following (Bruyn et al., 2018), the price of NH_3 emissions was set at €17.5/kgNH_3. The farm system heterogeneity is most evident for the clover measure. As shown in Table 7, clover is cost-beneficial for dairy and cattle farms, cost-effective for sheep and mixed livestock farms but cost-prohibited for the tillage farm. In a similar vein, while the covered stores' option is generally cost-effective for other farm systems, it is cost-beneficial for tillage. The slurry amendments option is cost-effective for the diary and tillage farms but cost-prohibited for all other farm types.

The mean MAC for ‘all farm’ ranges from -€27.35kg^{-1}NH3 to €34.85kg^{-1} NH3. All fertilizer options and the crude protein in diets are cost-beneficial while slurry amendments act as a cost-prohibited measure act as a cost-prohibited measure, the LESS and the covered stores are cost-effective. In contrast to all farm that ranks the inclusion of crude protein in diets as the second option, the clover is ranked as the second option for the dairy farm. This again indicates the presence of farm heterogeneity.

For the dairy farm MACC (Fig. 4), the diagram shows the cost-beneficial measures as liming, clover, crude protein, and protected urea. The cost-effective measures are covered stores, LESS and slurry amendments. All of the abatement options considered in this study can be implemented on the dairy farm to reduce ammonia emissions since no abatement measure is cost prohibited (that is, below the price of NH_3) with the marginal abatement cost ranging from -€30.03kg^{-1}NH3 to €16.57 kg^{-1} NH3. Apart from the difference in the position and class of abatement options between the dairy farm and all farm, the cost-effectiveness of the seven abatement measures for the dairy farm is slightly lower than the all farm (Total).

The ranking of abatement measures for the cattle farm follows closely that of the all farm, the significant difference between the cattle farm and the all farm is evident in the values of the cost-effectiveness across the abatement measure. The cattle farm reports a lower value for the cost-beneficial measures and a higher value for the cost-prohibited measure in contrast to the all farm. The MAC for the cattle farm ranges between -€26.91kg^{-1}NH3 to €41.83kg^{-1} NH3. The sheep and the mixed livestock farms rank abatement measures invariance to the other farm types. For both of the farm types, only three measures (liming, crude protein and protected urea) are cost beneficial and clover ranked sixth (as a cost-effective measure).

Table 7 NH3 Farm-level MAC across Different Farm Typologies

Cost-effectiveness NH3 (€ per kg abated)	**Specialist Dairy**	**Cattle**	**Specialist sheep**	**Specialist Tillage**	**Mixed Livestock**	**All farms**
1. Protected Urea	-0.04	-0.01	-0.02	-0.01	-0.02	-0.02
2. Liming	-30.03	-26.91	-19.47	-43.48	-17.31	-27.35
3. Clover	-22.59	-6.16	16.44	31.69	2.85	-2.40
4.Low emissions slurry spreading (LESS)	0.48	0.94	0.83	0.27	1.07	0.80
5. Slurry amendments	16.57	41.83	36.36	15.66	41.23	34.85
6. Reduction in crude protein	-21.55	-10.62	-8.96	-5.91	-12.48	-11.85
7. Covering of slurry stores	0.12	0.03	0.02	-0.10	0.01	0.03
* Combined Measures	-11.64	-10.05	-21.84	-43.66	-3.85	-14.52

Source: Authors Computation of 2020 NFS and NIR data

As shown in Table 7, is it at least cost-beneficial to interact with all the measures considered in this study, that is, the overall impact of combining the measures exhibits a synergistic relationship. The combined measure for all farms has a MAC of -€14.52 kg^{-1}NH3. For a detailed description of MAC distribution of farms across different farm systems see the Appendix.

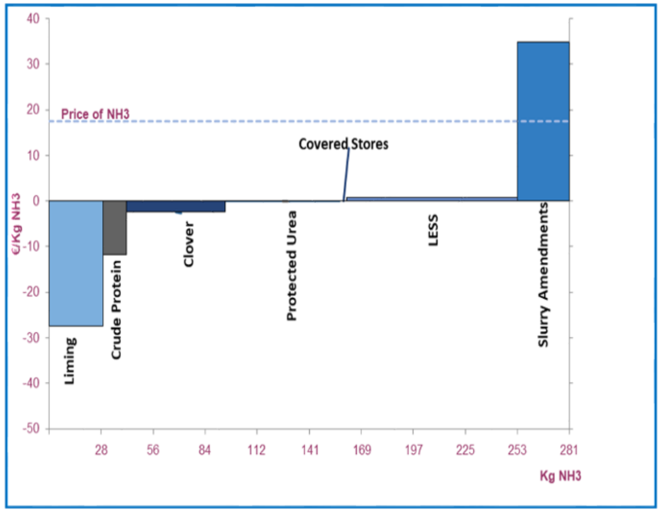

Fig. 3a. All farm

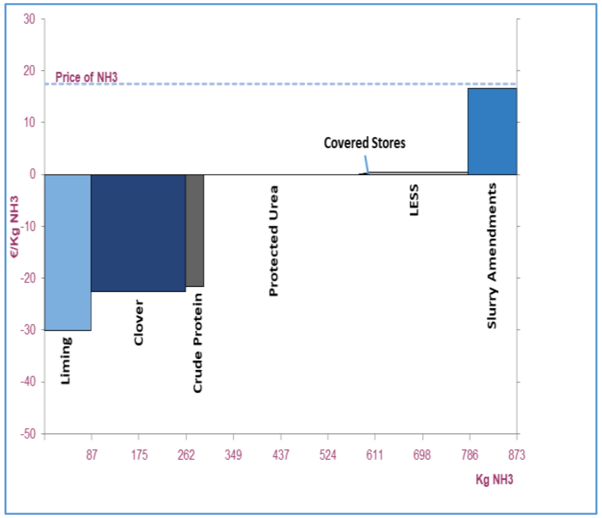

Fig. 3b. Dairy farm

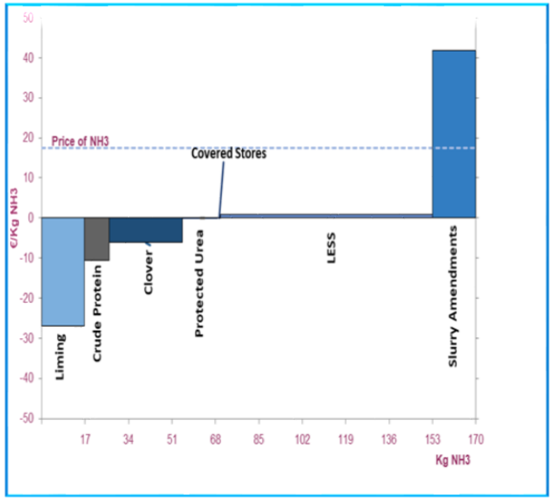

Fig. 3c.Cattle farm

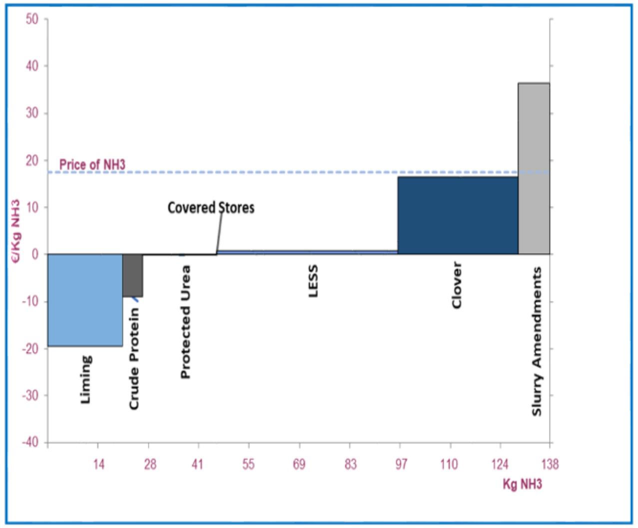

Fig.3d. Sheep farm

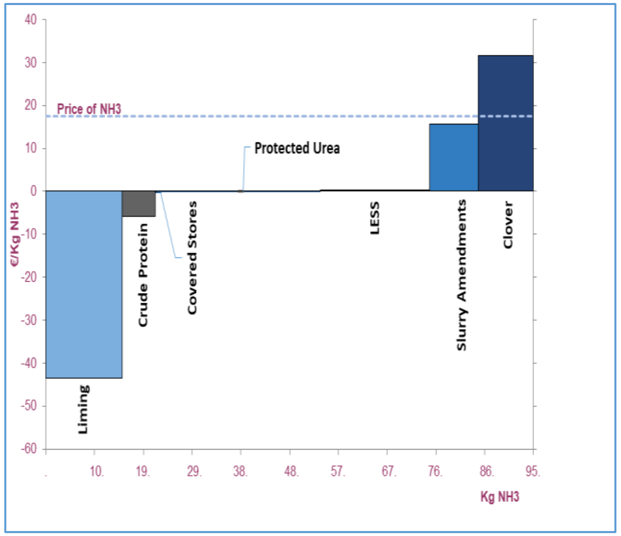

Fig. 3e. Tillage farm

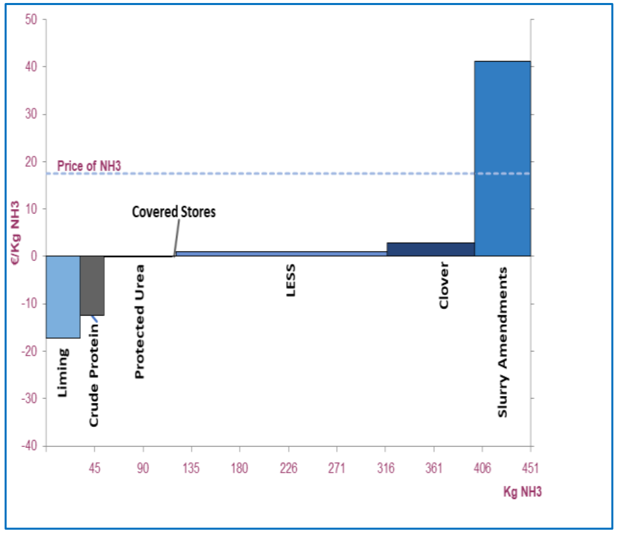

Fig. 3f. Mixed livestock farm

5. Discussion

While an extensive literature on GHG MACC exists, studies on NH_3 MACC are more limited, most especially studies investigating the distribution of NH_3 emissions across different farm systems. This is an important knowledge gap since heterogeneity being missed leading to inefficient policy decisions ….. This paper addresses this knowledge gap by assesing the NH_3 MACC across the individual farm system rather that an aggregate national level.

. The results of the analysis in this paper suggest that LESS delivered the highest level of NH_3 mitigation across all farm enterprises except Dairy and Tillage where protected urea was highest. The LESS measure remains a crucial measure in abating NH_3 emissions (Lalor et al., 2014; Wagner et al., 2017). Wagner et al. (2017) also recommend that LESS measures should be adopted by livestock farms to address ammonia emission reduction. The finding in our study is consistent with that of Buckley et al., (2020) who reported that the LESS measures have the highest abatement potential for NH_3 emissions at the national level for Irish agriculture. In their study the LESS measure was responsible for about 65% of the total ammonia abatement for the bovine categories. However, our study found that LESS reduced approximately 33% of all farm NH_3 emissions and about 45% for the cattle and mixed livestock farms. The contrast in these findings may be due to different levels of analysis used across both studies. It could also be that some farmers, especially dairy farmers, have already implemented the LESS measure in the baseline scenario. The result of the abatement potential of dairy farms shows that LESS measures account for the second-highest abatement potential. While for the specialist tillage farm, the higher concentration of arable farms to livestock could make the crop-based measure (protected urea) more suitable than the bovine measure. Farm system disaggregation provides additional insights into NH3 MACC analysis, for instance, policy recommendation on the use of LESS may place burden on tillage farms and including these in the overall analysis would understate the benefits of LESS for the other systems

Our result justifies the use of protected urea as an important strategy in reducing NH_3 emissions (Hristov et al., 2011), the use of the protected urea measure is reported in our study to be more efficient in dairy farms compared to some other farm categories. While (Hristov et al., 2011) reports the importance of protected urea (urease inhibitors) in abating ammonia emissions from both dairy and cattle feedlots, our results indicate a far greater efficiency of NH_3 abatement in the dairy farm system in contrast to the cattle farm system using protected urea. The high abatement potential reported for dairy farms may be attributed to the grass-based characteristics of Irish dairy farms; that is, grasses are used as the chief source of food for the dairy cows (Läpple et al., 2012; Läpple & Thorne, 2019), by replacing a huge proportion of the fertilizer necessary for the growth of dairy grasslands. Collectively LESS and protected urea alone accounts for more than half (>50%) of the NH3 reductions across the five farm categories.

The use of clover was also found to have relatively high abatement potential after protected urea for all farms. This results corroborates the report of Spink et al. (2019) who shared the importance of implementing white clover as an NH_3 abatement strategy, however, taking farm heterogeneity into cognisance, across the different farm systems the clover also exhibits varying levels of abatement potentials with the abatement potential for the dairy farm about sixteen times that of the tillage farm.

While Spink et al. (2019) posited that a 1% reduction in the N excretion rate results in about 3 to 6% NH_3 reduction, our resultfound that a 1% reduction in dairy N excretion leads to a decrease of approximately 1% in NH_3 emissions at the farm-level. Our result contradicts that of Kavanagh et al., (2019) who reported that slurry amendments are more favourable than the slurry spreading techniques and covering of slurry stores The difference in the result could be a result of conceptualization. For instance, their study involved the use of splash plate as land spreading technique or focused essentially on low emission slurry spreading (LESS) techniques. Also while their study encompassed ferric chloride, alum, sulphuric acid and acetic acid as slurry amendments, this study focused essentially on the use of aluminium sulphate (alum) as a slurry amendment strategy under this pathway due to the ease and safe use and application of the substance (Buckley et al, 2020).

Our MACC analysis for combined farm results in a different ranking of the abatement strategies compared to that of Lanigan et al.(2015) and Buckley et al. (2020). Buckley et al., (2020) ranked crude protein in diets as the most cost-beneficial measure (first measure) whereas this study ranked liming as the most beneficial measure. Liming in Buckley et al. (2020) was ranked 4th place. LESS was ranked as a more cost-effective measure to covered stores in Buckley et al., (2020) which is in contrast to the findings of this study. Webb et al. (2005) and Wagner et al. (2015) also affirmed the positive abatement cost of the LESS measure.

Lanigan et al (2015) ranked protected urea as a cost-effective measure as against this study or Buckley et al. (2015) who ranked protected urea as a cost-beneficial measure. Our result shared a similar view with Zhang et al. (2019) who reported crude protein in diets as a cost-beneficial measure under dairy production in China. Sajeev et al. (2018) also point out the importance of reducing crude protein in diets in abating ammonia emissions from cattle. This study shares similar findings for crude protein in diets and ammonia emissions under the cattle farm system. The use of crude protein in diets was also not cost-beneficial as against our finding, however, it is noteworthy that the use of crude protein in the diet in Lanigan et al., (2015) is on pigs farm system as against that of our study. This contradiction in the behaviour of crude protein under the dairy and pig system also points towards the importance of farm heterogeneity.

Wagner et al. (2017) firmly support the presence and importance of farm-system heterogeneity in explaining the potential abatement values of different strategies. Similar to our study a lower marginal abatement cost was recorded for the LESS measure for cattle and dairy systems compared to the mixed livestock and all farms, while our study reports a higher marginal abatement cost of covered stores for the dairy and cattle farms in contrast to the mixed livestock and all farms. The point of this discussion is that variation exists in the abatement potentials, cost of abatement and the marginal cost of abatement across different farm types, therefore it is very important to consider farm heterogeneity in policy recommendations.

Despite the variations across the farm typologies, some similarities can also be found. For instance, liming, protected urea and crude protein option are all cost-beneficial across the farm types These measures are highly appropriate for implementation across the different farm systems. However, the direct comparison of our findings is very limited, the difference in the ranking of measures with other MACC studies may be due to the difference in the level of analysis, basic underlying assumptions, baseline scenarios and regional scope.

Assessing the interactions amongst abatement measures is also important in order to understand the synergistic and antagonistic effects among these measures. Interaction can occur between two measures and amongst measures in abating ammonia emissions. This study focused on the interactions across all the seven abatement measures but did not go into specific details of the potential interactions between any two measures, for instance, crude protein and LESS measures**.** Unlike Pellerin et al. (2017) we also did not assume an additive nature of the abatement potentials. However an interaction among abatement measures was assumed through the simultaneous adoption of the abatement measures in the manure management chain..

As explained by Webb et al. (2005), abatement measures have some level of interactions and interdependence among them, as such accounting for the interactions without assuming additive figures of the abatement potentials and cost-effectiveness gives a truer estimate of the ammonia emissions reduced from the manure management chain starting from the crude protein to the land spreading stage. Eory et al. (2018) buttress the importance of accounting for interactions amongst abatement measures rather than cumulating the abatement potentials of measures, Wagner et al. (2015)

and Röder et al. (2015) report on the importance and the existence of interactions amongst abatement measures, Röder et al. (2015) in their study on GHG abatement support our findings that combining abatement measures leads higher abatement potentials but not necessarily at a lower cost as argued in their study.

Whether assuming an additive nature or not, studies have shown that accounting for interactions for MACC analysis has added advantage compared to the analysis of individual measures.

6.0 Conclusions

The assessment of farm-level MACC for NH_3 emissions was assessed in this study on an individualand combined basis. Also considered in this study was the influence of farm's heterogeneity on the abatement potentials, costs, cost-effectiveness and by extension the MACC curves.

The study showed that one type of MACC curve for all the different farm types may not necessarily represent the optimum abatement potential or MAC required by the farms. Furthermore, the study points towards the existence of a synergistic relationship amongst the abatement measures as evidenced by the increased abatement potential and overall cost saving scenario of the combined measure.

While this research focused on farm heterogeneity through the different farm typologies, farm regional differentials were not accounted for, thus further research should try to account for farm location as well as typology in constructing farm-level marginal abatement curve. Also, although the study accounted for dynamic relationships among the abatement measures through interactions within the measures, it did not account for dynamic relationships through time due to the lack of a farm-level model that can project activity data into the future.

Even though the aforementioned research has shown that abatement measures are effective in reducing ammonia emissions, previous work has shown that they may also be effective in abating greenhouse gas emissions, thus the full impact of these measures in mitigating both NH_3 and GHG emissions simultaneously represents an avenue for future research.

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APPENDIX

The Assumptions and Rationale for Selecting Abatement Measures

The mitigation measures included in the analysis are outlined below:

1. **Protected Urea:** Chemical N fertiliser in the form of straight urea (46% N generally) is the cheapest source of chemical N fertilizer but has the highest level of ammonia (NH_3) emissions (Abalos et al., 2012; Schraml et al., 2016). The use of protected urea, which is based on urea fertilizer treated with N-(n-butyl) thiophosphoric triamide (NBPT) can mitigate both NH_3 and nitrous oxide (N_2O) emissions (Abalos et al., 2012; Nkwonta et al., 2021; Bobrowski et al., 2021) and increase nitrogen uptake by crops. The rationale behind using protected urea as an abatement measure is well established (Forrestal et al., 2016; Schraml et al., 2016; Buckley et al., 2020; Bobrowski et al., 2021).[2]

   In this scenario analysis, it is assumed that all straight urea used on farms was replaced fully by protected urea.

2. **Liming:** The application of lime on acidic soils (characteristics of most of the Irish soils) increases soil pH and contributes to the plants' absorption of nutrients, minimizes the spread of plant diseases, forms better soil moisture, soil structure and aeration for plants (Nadeem et al., 2020). Previous studies have indicated that liming reduces the need for inorganic fertilizers and consequently ammonia emissions (Lanigan et al., 2015; Buckley et al., 2020). The application of lime was ranked as one of the most effective abatement measures for both Irish agriculture (Buckley et al., 2020) and Scottish agriculture (Eory et al., 2021).

   Based on a subset of nationally distributed soil sample results of the Irish Agricultural and Food Development Authority 2019 report (Teagasc 2019) showed that on average 46% of dairy farms, 50% of cattle and sheep farms and 22% of tillage farms have sub-optimal soil pH where the optimum soil pH of Irish agricultural soil is 6.2. Results are available by farm system (dairy, dry stock, tillage) and by soil ph band (e.g. 6.2-5.9, 5.9-5.5 and <5.5). These nationally generated results are assumed to apply to the soil status of farms in our sample, stratified by farm system. Based on Irish specific soil experiments (Wall, 2020) it is assumed that 1 tonne of lime applied per hectare increases the pH by between 0.15-0.2 units depending on the starting pH of the soil.

   It is assumed that all sub-optimal soils are treated with the recommended rate of lime (Teagasc ref) and that 80 kg of nitrogen is released per hectare in this process (Teagasc, 2021). It is also assumed that the lime cost €25 to apply per tonne (Buckley et al., 2020) and that a soil sample is taken across every 3 hectares of the farm to establish base levels of soil fertility. The effect of liming is estimated to last 5 years; hence costs are discounted over this period (Teagasc, 2021).

3. **Clover:** Extensive literature exists on using clover as a strategy in the gaseous emissions area (Spink et al., 2019; Buckley et al., 2020; Eory et al., 2020). The importance of using clover as an abatement practice can be attributed to its natural fixation of nitrogen which reduces the need for chemical fertilization, thus reducing emissions from chemical fertilizer application (Buckley et al., 2020; Eory et al., 2020). Spink et al. (2019) affirmed that an inverse relationship exists between gaseous emissions and biologically fixed nitrogen from the use of white clover.

   In this study, it is assumed that all grassland areas of the farms were reseeded with clover with that replaced a maximum of 80kg of chemical N per hectare. Where fertilisation rates are below this it is assumed half of all chemical N is replaced. The costs of implementing this mitigation measures are based on contractors

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[2] NBPT is a urease inhibitor. A urease inhibitor moderates the rate at which urea converts to ammonium. In so doing, ammonia loss is reduced to low levels.

rates of €116.14 per hectare for reseeding of grassland with clover (FCI, 2020) and the cost per hectare of clover seed is €50.

4. **Low Emission Slurry Spreading (LESS):** The most common method of applying liquid based animal manure (slurry) is the use of a splash plate. This method broadcasts the slurry over a wide area. Alternative application methods exist under the broad label of Low Emission Slurry Spreading techniques (LESS). LESS consist of the use of slurry injection, trailing hose and trailing shoe, which reduces ammonia emissions in place of splash plates.

   The LESS methods are based on the principle of reducing the area of the ammonia emitting surface. In the case of LESS the liquid manure is applied directly to the soil/plant surface which can reduce ammonia emissions by more than 50% when compared to emissions associated with the use of splash plate methods (Thorman et al., 2008; Buckley et al., 2020). The trailing hose reduces the ammonia volatilisation surface area by depositing slurry on top of the grass in bands rather than broadcasting over a larger surface area, while the trailing shoe application reduces the ammonia volatilising surface area by depositing slurry on the soil surface, underneath the grass. The use of the LESS method as a mitigation option is an accepted mitigation practice across developed countries (Wagner et al., 2017).

   This scenario was developed based on the assumption that 100% of slurry is applied by splash plate in the base year was substituted to LESS, which a 50/50 split between trailing shoe and trailing hose methods. The ammonia emission factor for trailing shoe and hose are 30% and 60% of that for splash plate application, respectively (Bittman et al., 2014). Following the approach by Buckley et al. (2020), costs are estimated based on relative contractor rates for application which suggests that using a 11500-litre tanker, the cost of slurry spreading by splash plate and LESS method is €65/hour and €85/hour respectively.

5. **Covering of Slurry Stores:** Some studies have applied the use of slurry covers to abate ammonia emissions. These reported that the covering of slurry led to a significant reduction of NH3 emissions (Zhang et al., 2019; Buckley et al., 2020) and GHG emissions (Eory et al., 2020). Zhang et al. (2019) buttressed that the adoption of covered slurry reduced NH_3 emissions by 4-49% in China compared to their baseline scenario of no abatement. NH_3 reduction at the slurry storage stage leads to higher nitrogen retention for use within the farm system. This in turn reduces the requirement for chemical nitrogen fertiliser for a given level of agricultural production. All cover types were posited to reduce NH_3 emissions (Kupper et al., 2020); see Reis et al. (2015) for further information on slurry cover types and their ammonia reduction efficiencies.

   The assumptions behind the adoption of the covering of slurry stores are based on the use of a flexible floating cover and an implementation rate of 100% (that is, it involves moving all uncovered stores to covered stores). The emissions factors for covered stores is 50% lower than for uncovered slurry stores.

   Based on the report of Reis et al. (2015) a cost of €1.5 per m^3 of slurry is assumed to replace an open slurry store with a covered slurry type with the cost discounted over 10 years.

6. **Slurry Amendments:** The emissions of NH_3 during the slurry storage stage can be offset by the inclusion of chemical amendments (Kavanagh et al., 2019). These amendments may include such compounds as alum, ferric acid, sulphuric acid and acetic acids. They work by lowering the pH of slurry during storage through a process called acidification (Kavanagh et al., 2019). This mitigation scenario is based on the assumption that compound alum is the treatment added to the bovine slurry and that this reduces NH_3 emissions at the slurry storage stage by 70% (Buckley et al., 2020) with a 100% adoption rate assumed among farmers. The adoption of the slurry amendment leads to a reduced requirement for chemical fertilizer due to the increased quantity of nitrogen captured in the slurry and later returned to the soil at the land spreading stage of the manure management chain. The cost per volume of slurry amendments is assumed to be €2.34 per m^3 and €4.40 per m^3 for dairy and cattle slurry, respectively (Kavanagh et al., 2019) .

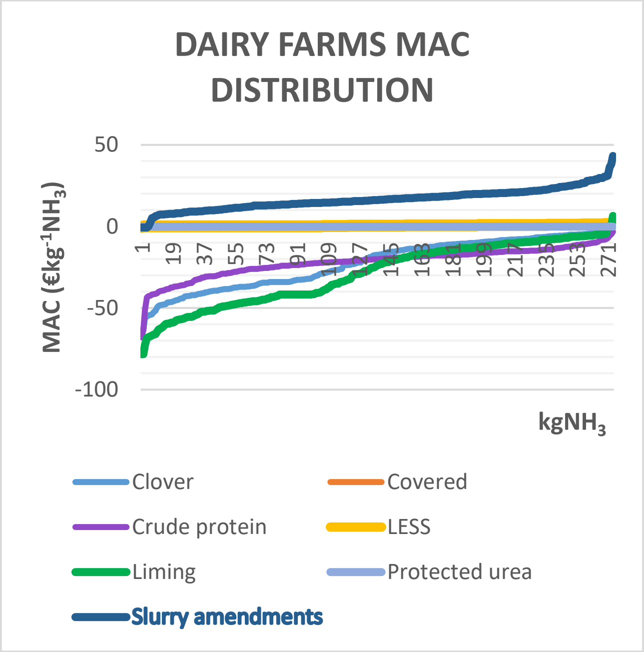
7. **Crude protein in diets:** Excess crude protein (over requirement) in the diet of bovines and pigs leads to higher N excretion rates and ultimately higher ammonia emissions (Sajeev et al., 2018; Buckley et al., 2020). This abatement measure works by influencing the amount of nitrogen excreted by livestock and by extension those entering the manure management chain (Buckley et al., 2020). Excessive nitrogen is essentially blocked from entering the farm system. It is assumed that the average dairy cow is fed 1,045 kg of concentrates (Buckley et al., 2020). Furthermore, it is assumed that a 1% decrease in the crude protein composition of dairy concentrates leads to a decrease of 1.5 kg in the N excretion rate of dairy cows (O'Brien & Shalloo, 2019). This decrease in the crude protein composition of dairy cows diet also leads to a cost reduction of €6 per ton of dairy concentrates (Patton, 2020).

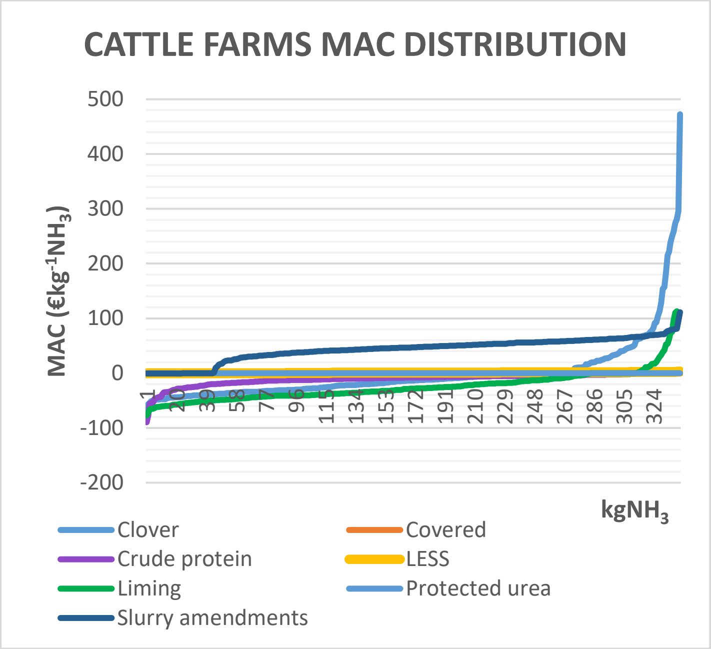
Table 8 Detailed Description of Ammonia Emissions, Cost and Cost-Effectiveness

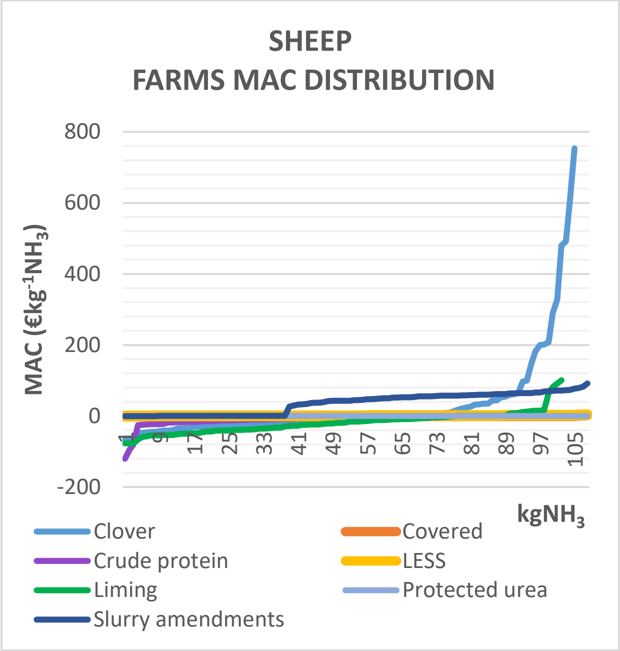
Abatement Measure	Farm System	Specialist Diarying	Cattle farms	Specialist Sheep	Specialist Dairy	Mixed livestock	Total
PROTECTED UREA	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2579.73	730.18	504.31	563.33	1738.77	1007.57
	Abatement Potential	287.07	13.94	20.30	32.15	63.60	62.28
	Cost of Abatement	-€23.77	-€1.15	-€1.68	-€2.66	-€5.27	-€5.16
	Cost-effectiveness	-€0.04	-€0.01	-€0.02	-€0.01	-€0.02	-€0.02
LIMING	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2780.41	727.42	504.07	580.65	1770.60	1040.91
	Abatement Potential	86.39	16.69	20.55	14.84	31.77	28.94
	Cost of Abatement	-€1,336.97	-€398.61	-€337.49	-€517.36	-€686.66	-€558.35
	Cost-effectiveness	-€30.03	-€26.91	-€19.47	-€43.48	-€17.31	-€27.35
CLOVER	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2692.33	715.41	491.53	584.75	1721.14	1016.73
	Abatement Potential	174.47	28.71	33.08	10.74	81.23	53.11
	Cost of Abatement	-€2,121.18	-€411.82	-€225.04	-€64.30	-€1,061.45	-€651.54
	Cost-effectiveness	-€22.59	-€6.16	€16.44	€31.69	€2.85	-€2.40

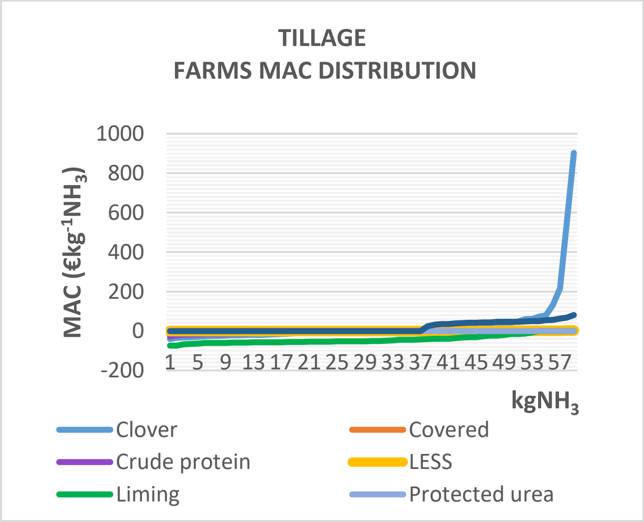
Table 7 Detailed Description of Ammonia Emissions, Cost and Cost-Effectiveness

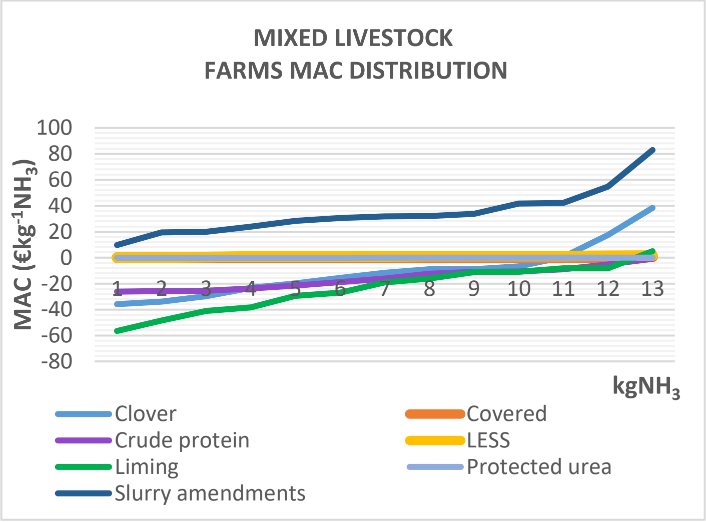
Abatement Measure	Farm System	Specialist Diarying	Cattle farms	Specialist Sheep	Specialist Dairy	Mixed livestock	Total
LESS	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2683.06	660.90	475.09	574.07	1606.09	977.65
	Abatement Potential	183.74	83.21	49.52	21.41	196.28	92.19
	Cost of Abatement	€126.92	€102.18	€67.64	€33.29	€202.47	€97.76
	Cost-effectiveness	€0.48	€0.94	€0.83	€0.27	€1.07	€0.80
SLURRY AMENDMENTS	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2775.47	727.19	515.74	585.96	1750.59	1041.77
	Abatement Potential	91.33	16.92	8.87	9.52	51.78	28.08
	Cost of Abatement	€1,409.84	€767.08	€460.17	€394.45	€1,526.55	€812.72
	Cost-effectiveness	€16.57	€41.83	€36.36	€15.66	€41.23	€34.85
CRUDE PROTEIN	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	New Scenario emissions (kgNH3)	2833.73	734.46	519.30	588.88	1780.15	1056.98
	Abatement Potential	33.06	9.66	5.31	6.60	22.22	12.86
	Cost of Abatement	-€745.16	-€105.76	-€59.93	-€68.23	-€385.96	-€206.80
	Cost-effectiveness	-€21.55	-€10.62	-€8.96	-€5.91	-€12.48	-€11.85
COVERED STORES	Baseline Adoption of measure						
	Baseline emission (kgNH3)	2850.96	743.23	524.53	595.36	1798.81	1066.63
	New Scenario emissions (kgNH3)	2866.80	744.12	524.61	595.48	1802.37	1069.84
	Abatement Potential	16.48	0.89	0.09	0.12	3.77	3.33
	Cost of Abatement	€7.89	€0.82	€0.06	-€0.04	€2.20	€1.83
	Cost-effectiveness	€0.12	€0.03	€0.02	-€0.10	€0.01	€0.03


DAIRY FARMS MAC DISTRIBUTION
MAC (€kg-1NH3)
50
0
-50
-100
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
kgNH3
Clover
Covered
Crude protein
LESS
Liming
Protected urea
Slurry amendments


CATTLE FARMS MAC DISTRIBUTION
MAC (€kg-1NH3)
500
400
300
200
100
0
-100
-200
1
20
39
58
77
96
115
134
153
172
191
210
229
248
267
286
305
324
kgNH3
Clover
Covered
Crude protein
LESS
Liming
Protected urea
Slurry amendments


SHEEP FARMS MAC DISTRIBUTION
MAC (€kg-1NH3)
800
600
400
200
0
-200
1
9
17
25
33
41
49
57
65
73
81
89
97
105
kgNH3
Clover
Covered
Crude protein
LESS
Liming
Protected urea
Slurry amendments


TILLAGE FARMS MAC DISTRIBUTION
MAC (€kg-1NH3)
1000
800
600
400
200
0
-200
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
kgNH3
Clover
Covered
Crude protein
LESS
Liming
Protected urea


MIXED LIVESTOCK FARMS MAC DISTRIBUTION
MAC (€kg-1NH3)
100
80
60
40
20
0
-20
-40
-60
-80
1
2
3
4
5
6
7
8
9
10
11
12
13
kgNH3
Clover
Covered
Crude protein
LESS
Liming
Protected urea
Slurry amendments