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

Prepared by Teagasc's Special Working Group on Abatement Totals
(part of the Teagasc Greenhouse Gas Working Group):

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Executive Summary

This submission has been prepared by Teagasc in response to a request by the Department of Agriculture, Food and the Marine to provide an analysis of the potential to abate national ammonia (NH_3) emissions. This current report follows on from a previous analysis where Teagasc quantified the abatement potential of a range of greenhouse gas (GHG) mitigation measures, as well as their associated costs/benefits. The objective of the analysis is to quantify the extent and costs associated with meeting future ammonia emission targets that were negotiated as part of the amended Clean Air Policy Package.

The requirement to reduce ammonia emissions is not only urgent in the context of Clean Air legislation, but as a principal loss pathway for agricultural nitrogen, it should be a key focus for improving farm efficiency and sustainability. This is particularly relevant in the context of Food Harvest 2020 and the new Food Wise 2025 Strategy which sets out a strategy for the medium-term development of the agri-food sector.

Under the Food Wise 2025 Sustainable Growth Strategy developed for this report, agricultural ammonia emissions are projected increase by 6% by 2030 relative to 2005 levels. While these increases are small in comparison to the targeted increase in agricultural output, they will provide a significant challenge to meeting emissions targets, particularly as agriculture comprises 98% of national emissions. The analysis presented in this report uses a Sustainable Growth Scenario, which seeks to achieve a balance between the type of growth envisaged in Food Wise 2025 and the pressures to limit emissions. The study assesses the additional potential for ammonia abatement by 2030 and the potential impacts on other nitrogen (N) emissions.

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

Compared to a future where no measures are deployed to address emissions, by 2030 the *maximum technical abatement* potential was estimated to be between 10.6 and 12.05 kT NH_3. This will result in 2030 emissions of 101.8 – 103.2 kt NH_3 representing a 5.1% reduction relative to the 2005 **agricultural** ammonia emissions.

While this maximum abatement falls short of the initially proposed 2030 targets (10% reduction relative to 2005) it achieves the amended 5% target. In nominal terms the cost of achieving this abatement was estimated at between €29 and €35.6 million per annum. It should be stressed that this is an assessment of the maximum abatement potential. Realising this level of abatement in practice would be extremely challenging and would require the use of significant policy levers.

The analysis also revealed few very cheap or cost-effective mitigation options. Only measures such as altered slurry timing and altered crude protein of pig diets had the potential to be cost-neutral or cost beneficial. Furthermore *cost-effective ammonia abatement was estimated to be 8.2 - 9.8 kT NH_3 at a total cost of €17.6 million per annum,* if only measures at or below €5,000 per tonne NH_3-N abated were considered. It was noted that costs are highly sensitive and may increase or decrease with factors such as N replacement value.

Glossary and Definitions

Activity data	Data that quantify the scale of agricultural activities associated with emissions at a given moment in time. Activity data are expressed as absolute numbers (e.g. number of dairy cows, national fertiliser N usage) and typically change over time.
Food Wise 2025	Food Wise 2025 – a strategy document for sustainable growth in Irish agriculture developed by food industry stakeholders in 2015
ATMS	Altered Timing Management System, or altered timing of slurry application
Biophysical constraint	Limitation, set by the natural environment, which is difficult or impossible to overcome. Example: "the use of bandspreading equipment for slurry spreading in spring is biophysically constrained to well-drained and moderately-drained soils, and is excluded from poorly-drained soils due to poor soil trafficability allied to increased weight of the bandspreaders".
CLRTAP	The Convention on Long-range Transboundary Air Pollution was the first international legally binding instrument to deal with problems of air pollution on a broad regional basis. It was signed in 1979 and entered into force in 1983. It has since been extended by eight specific protocols. These include the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone which covers ammonia emissions.
Emission factor	Established numbers that quantify the emissions associated with activity data (see above), and that are expressed as "emissions per activity unit", e.g.: ammonia emissions per kg N applied. Generally, the values of emission coefficients do not change over time, unless more accurate/representative values are obtained by new research.
EPA	Environmental Protection Agency (Ireland)
EU	European Union
FAPRI-Ireland	Collaboration between Teagasc and the Food and Agricultural Policy Research Institute at the University of Missouri
FH 2020	Food Harvest 2020
GHG	Greenhouse Gas
Gothenburg Protocol	The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (known as the Multi-effect Protocol or the Gothenburg Protocol) is a multi-pollutant protocol designed to reduce acidification, eutrophication and ground-level ozone by setting

	emissions ceilings for sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia to be met by 2010.
kt	Kiloton (1,000,000 kg)
MACC	Marginal Abatement Cost Curve
M€	Million euro
N	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NECD	National Emissions Ceilings Directive
SGS	Sustainable Growth Scenario: In order to mitigate potential environmental impacts arising from increased output and production associated with FW2025 there is a recognition that environmental protection and sustainability will need to be central to any increases in production. This scenario achieves production targets via optimising agricultural activity
TAN	Total Ammoniacal Nitrogen, the proportion of mineral N in animal excreta
TFEIP	Task Force on Emissions Inventories and Projection
UNECE	United Nations Economic Commission for Europe

Acknowledgements

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Contents

1. Introduction

1.1: Background

Ireland is a Party to the Convention on Long-Range Transboundary Air Pollution (CLRTAP), under which certain transboundary air pollutants are targeted for control (UNECE, 1999). As a member of the European Union (EU), the country is also subject to the National Emission Ceilings Directive (NECD) (EU, 2001), which implements the Gothenburg targets for EU member states. One of these pollutants is ammonia (NH_3), an acidifying gas that readily combines with nitrate and sulphate in acid cloud droplets (Asman et al., 1998) and returns to the soil as acidic depositions leading to both terrestrial and aquatic eutrophication and indirectly to nitrous oxide emissions (a greenhouse gas). Target emissions for Ireland to be achieved by 2010, under the NECD, were 116 kt NH_3 (Humphreys, 2008). However, both the Gothenburg Protocol and the EU National Emissions Ceilings Directive were reviewed in 2012 with a new target of a 0.5% reduction in ammonia emissions relative to 2005 levels by 2020 (DAFM, 2013). Furthermore, a proposed amendment to the NECD will also impose a further reduction target for 2030. Under the EU Clean Air Package, the European Commission plans to propose cuts to ammonia emissions in the overall EU agricultural sector by 19% by 2030, with Ireland's effort sharing target of this reduction determined at -5% of 2005 levels.

1.2 Ireland's Emissions Profile

Irish agriculture contributes virtually all (98%) of Ireland's national ammonia emissions (Hyde et al., 2003; Duffy et al., 2015). Historical Irish emissions are shown in Figure 1.1. Agricultural ammonia emissions reached a peak of 130 kt in 1998 but have since declined to 105 kT NH_3 in 2014, due to a decline in the ruminant livestock population and reduced use of fertiliser nitrogen (N). In 2014 dairy and non-dairy bovines comprise 76.9% of agricultural ammonia, with these emissions arising principally from animal housing and storage (41.4%) and the landspreading of manures (28.6%). Manure emissions from pig and poultry systems comprise the bulk of the remaining emissions, followed by fertiliser-based emissions. These fertiliser emissions have declined over the period 1990 to 2013, due to a combination of reduced fertiliser use and a lower proportion of urea within total fertiliser use.

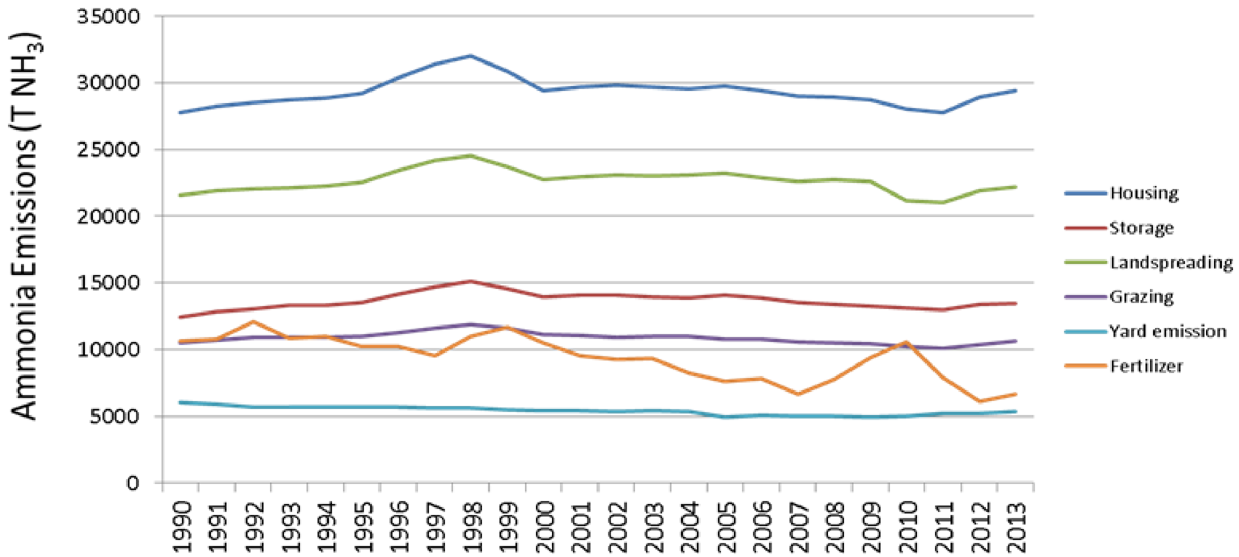

Figure 1.1: The composition of Irish national agricultural ammonia emissions: The contribution of various farm activities (data: EPA)

Irish agriculture is dominated by pastoral bovine livestock production, with approximately 90% of the utilisable agricultural area in Ireland comprised of permanent grassland. This dictates the farming system and also defines to a large extent the ammonia abatement practices available.

Typically livestock in Ireland are fed a grass based diet (grazed grass and grass silage) and spend about 60% of their time on pasture. As a result N excreted on pasture accounts for 61% of total N excretion, compared to 8% for Denmark, 10.6% for Germany and 13.6% for the Netherlands (Figure 1.2).

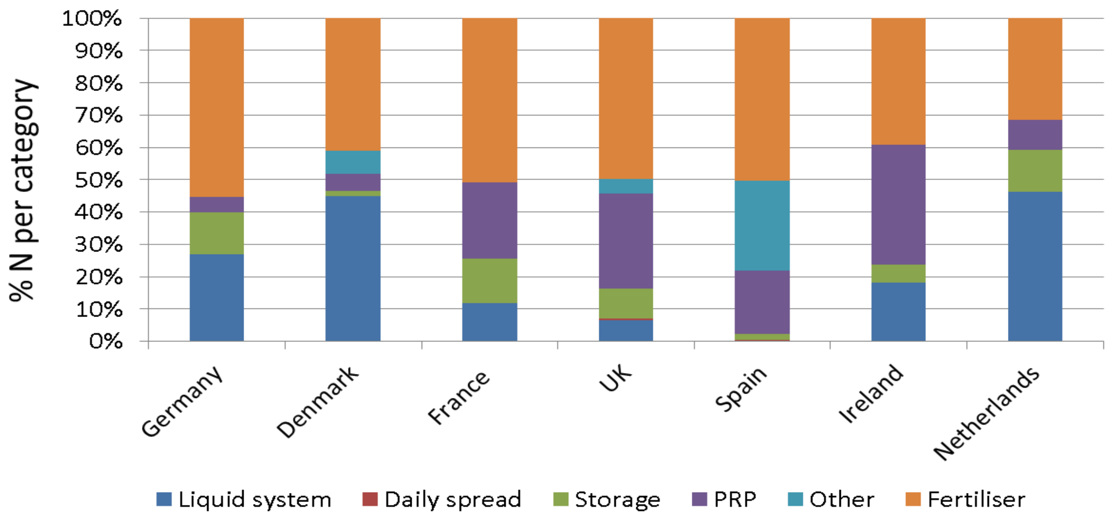

Figure 1.2: The percentage allocation of agricultural N between various agricultural activities for several EU countries (Source UNECE 2015)

This has resulted in comparatively low Irish national emissions both in absolute terms and in terms of applied agricultural N (8.8%) lost as ammonia, comparing favourably with other large EU agricultural producers (Figure 1.3). This arises due to the fact that the ammonia emissions factor associated with grazing is 6% of applied ammoniacal N. In contrast, housing and the storage of livestock slurries and manures have reported N losses ranging from 3 to 60% of initial total N (Muck and Steenhuis, 1982, Hartung and Phillips, 1994), with variations due to animal type, housing/storage type and climatic conditions. Indeed, grazing has been classified as a cost-effective Category 1 abatement technique in the Guidance Document For Preventing and Abating Ammonia Emissions from Agricultural Sources (Bittman et al. 2014). In order to further illustrate this point, if Ireland were to have grazing levels similar to Denmark (8%) or Germany (13%), ammonia emissions would be between 27 – 30 kT NH_3 higher than current emissions.

However, this high proportion of grazing results not only in low existing ammonia emissions, but a somewhat challenging task to achieve further ammonia abatement.

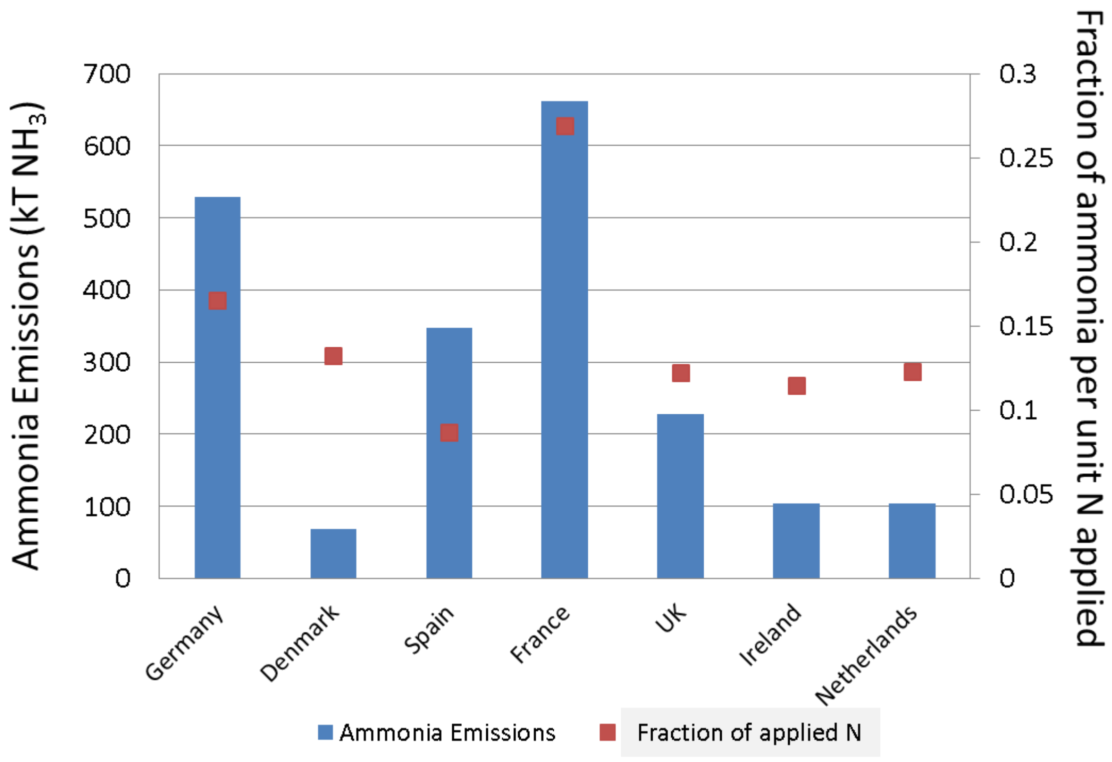

Figure 1.3: Irish National ammonia emissions and the fraction of N lost as ammonia for several EU countries.

This is due to the fact that the capacity to further extend grazing in Ireland will be limited as many farmers have already sought to maximise the grazing season for economic reasons. Indeed, an analysis of Irish ammonia abatement potential using the GAINS model has shown that in terms of grazing, Irish agriculture is already at 100% of maximum feasible abatement (Amann et al. 2011). In addition, the current configuration of Irish animal housing makes abatement challenging, with the majority of slurry in Irish cattle and pig slurry-based housing systems stored under the animals in slatted tanks, with a minority stored in open or closed tanks outside the buildings. In straw bedding systems the manure is stored under the livestock and is often spread directly from the house to the land. The very high proportion of grazing, combined with these under-slat housing and storage systems, result in systems that are not well suited to further significant ammonia abatement.

As a result, reductions in emission ceilings will pose considerable challenges in the context of largely grassland enterprise based expansion as envisaged under both Food Harvest 2020 and more recently, the Food Wise 2025 Strategy (FW2025).

2. Policy Context

The abatement and cost analysis presented here was conducted against the background of Irish national policies and strategies for expansion of the agricultural sector in Ireland. The current strategy for the sector, Food Harvest 2020 (DAFM 2010) was an industry-led initiative that sets out a strategy for the medium-term development of the agri-food sector. It identified the opportunities and challenges facing the sector and the actions needed to optimise profitability and further the sustainable production of Irish food. Overall targets included an increase in the value of primary output in the agriculture, fisheries and forestry sector by €1.5 billion. Specific growth targets included a 50% increase for milk volume, following the abolition of milk quota in 2015, as well as a 20% increase in the total value of beef produce.

This development plan has been further extended under the Food Wise 2025 Strategy, which envisages a further increase in dairy production as well as significant expansion of the arable, pig, poultry and forestry sectors. However, this expansion will have to be carried out whilst maintaining environmental sustainability. Indeed, the strategy has adopted as a guiding principle that "… *environmental protection and economic competiveness will be considered as equal and complementary, one will not be achieved at the expense of the other*." Sustainability is understood to encompass economic, social and environmental attributes and the subsequent strategic environmental assessment of FW 2025 proposed the need for a Sustainable Growth Strategy (SGS). The definition of this sustainable growth scenario recognises the need to achieve a balance between economic, environmental and social objectives. The SGS should seek to increase the value added by the sector per unit of emissions (GHG or ammonia) produced.

As stated earlier, Ireland's target for ammonia emissions under the current (revised Gothenburg) NECD is a 0.5% reduction on 2005 levels by 2020. Under the amended NECD of the Clean Air Package (Dec 2013), the Commission initially proposed a reduction for Ireland of 10% to 98.8 kT NH_3. This was later amended by Directive 2016/2284 to a 5% reduction in ammonia to 104 kT NH_3. In the context of the proposed 2030 NECD targets, cost-effective abatement of ammonia will be vital to maintaining this strategic vision.

2.1 Future Ammonia Emissions under the Food Wise 2025 Sustainable Growth Scenario.

The FAPRI-Ireland model (Donnellan & Hanrahan, 2006; Binfield et al., 2009) has been used extensively in the analysis of agricultural and trade policy changes in Ireland over the last 15 years. Using the FAPRI-Ireland model, Donnellan & Hanrahan (2011) had previously assessed the impact of Food Harvest 2020 on animal numbers and fertiliser use in order to estimate future agricultural GHG emissions in conjunction with the EPA. In this analysis, the model was used to assess the impact of the Sustainable Growth Scenario on levels of agricultural production and to determine the associated level of input usage. In this scenario, production increases over the period to 2025 to give higher levels of production by 2025 than previously projected under Food Harvest 2020 scenarios analysed (Donnellan and Hanrahan 2015).

Bovines: The projected output levels under the scenario reflect an increase in activity in the dairy sector following the removal of the milk quota system. Modelled outputs under the FW 2025 SGS also indicate a stable level of beef production (in tonnes of carcass produced, Table 2.1) over the medium term. However, the number of suckler cows is projected to contract over the medium term. Overall, the scenario projects a relatively stable cattle population and an increase in milk production. The overall cow population is projected to decrease by 3% by 2030 relative to the 2012-14 reference period (Table 2.1). Over the period to 2030 projected growth in the dairy cow herd is matched by the projected decline in the suckler herd.

Sheep: No major developments over the medium term are projected in the sheep sector. The historic decline in ewe numbers has already been arrested, with stable year to year developments in total breeding sheep numbers observed from 2010 to 2014. Ewe numbers are projected to decline moderately over the horizon period.

Pigs: The sow herd is projected to grow in the short term and then remain stable through the rest of the period. Continuing improvements in sow productivity (piglets per sow per year) will also lead to continued growth in the number of pigs available for slaughter over the horizon period. In addition there is growth in the slaughter weight of finished pigs. As a result of the combination of these effects, Irish pig numbers and pig meat production are projected to increase over the horizon, with pig numbers increasing by 24% over the period to 2030 (Table 2.1).

Poultry: Under the SGS the volume of Irish poultry production is projected to increase strongly over the medium term. The strong growth in Irish production is largely in line with projected growth in the domestic use of poultry in Ireland.

Fertiliser: While fertiliser use is projected to increase, the growth in the level of total fertiliser applied is quite limited under the SGS. While the more fertiliser intensive dairy sector increases its production, the area allocated to dairy also increases, so that the overall stocking rate exhibits little change. In addition, the price of feed relative to fertiliser declines, making purchased feed marginally more attractive economically than grass as an energy source and limiting the increase in the intensity of fertiliser use on a per hectare basis.

Ammonia emissions associated with different sub-sectors and activities were subsequently generated by inputting these activity data into EPA national ammonia inventories (EPA 2015) and extending this out to 2030.

Table 2.1: Activity data underlying the Food Wise 2025 Sustainable Growth Scenario out to 2030

Activity		% change by 2030 compared to reference years
	Reference Years	**Food Wise 2025 Sustainable Growth Scenario**
Total Cattle	2012-2014	-3%
Dairy Cows	2012-2014	+30%
Other Bovines	2012-2014	-10%
Total Sheep	2012-2014	-14%
Total Pigs	2012-2014	+23%
Milk (Million kg)	2011-2013	+66%
Beef Production (tonnes)	2012-2014	+1%
Poultry	2012-2014	+28%
Fertiliser Use (Tonne N)	2012-2014	+22%

Note: Increases to be achieved by 2025 are with respect to a historical reference, which is calculated as the average of 3 years' historical production.

3. Abatement of ammonia emissions

Abatement options for ammonia reduction at the various stages of livestock manure production and handling is interdependent, and combinations of measures are not simply additive in terms of their combined emission reduction capacity. Controlling emissions from applications of manures to land is particularly important, because these are generally a large component of total livestock emissions and because land application is the last stage of manure handling. Without abatement at this stage, much of the benefit of the abatement achieved during housing and storage, which is often more costly, may be undone. Emissions from the intensive pig and poultry sectors are significantly lower than from cattle, and are addressed within current Integrated Pollution Prevention and Control (IPPC) legislation and controls (Anon, 2003). Therefore, there is greater urgency for improvement of knowledge of emissions and abatement strategies in the cattle sector.

3.1: Factors controlling ammonia emissions

Typically livestock use less than 30% of N in their feed, with 50% to 80% of the remainder excreted in urine and 20% to 50% in the dung. Urea is the major form of N in urine accounting for 97% of N (McCrory and Hobbs, 2001). The concentration and form of N in cattle slurry varies according to diet, animal species and age (McCrory and Hobbs, 2001). As a result, crude protein levels influence both the total amount of N excreted and the proportion of N in urine and faeces. In housing systems, ammonia in manure is formed by the hydrolysis of urinary urea and is catalysed by microbial urease that is present in faeces. The enzymatic decomposition of urea into carbonic acid and volatile ammonia is initiated when urine and faeces contact one another after excretion. Other factors that influence volatilisation rates include controlling the NH_4+/NH_3 equilibrium of the NH_4^+-N concentration in the slurry. Also ventilation rates influence volatilisation via changes in concentration gradients.

Upon landspreading, temperature, windspeed and infiltration rate of slurry into the soil are the principal drivers of emissions. As a result, reducing slurry surface area exposure to external conditions results in lower emissions.

3.2 Selection of measures

Numerous agricultural mitigation measures for ammonia abatement have been reported in the international literature (Misselbrook et al. 2004, Reis et al. 2015, Bittman et al. 2014). The Guidance Document For Preventing and Abating Ammonia Emissions from Agricultural Sources was produced ‘to provide guidance to the Parties to the Convention in identifying ammonia (NH_3) control measures for reducing emissions from agriculture’. These guidelines divide abatement options into three categories:

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

Category2: Techniques and strategies which are promising, but research are currently inadequate, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of an NH_3 abatement strategy, depending on local circumstances and

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

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

Many housing/storage options were not considered, primarily due to configuration of Irish housing systems (under-slat tanks), which made many technologies impractical in an Irish context. For example, acidification of stored slurry is highly effective but would require the re-fitting of all storage systems in Ireland at a cost of €30,000 to €80,000 per farm. However expansion in the dairy industry will result in a move away from slatted tank options to slurry storage mechanisms where slurry is stored external in large over ground steel tanks, plastic lined lagoons and concrete built tanks all of which are more feasible with expanding herd sizes. Where in some cases there was no Irish specific information, it was decided that it was inappropriate to simply adopt the abatement potential, or costs from other countries. Therefore, for the MACC curve presented in this report, individual measures were selected and included on the basis of the following criteria:

- Measures must be applicable to farming systems common in Ireland;
- Scientific data, from completed research, must be available on the relative abatement potential of each measure, as well as the relative cost/benefit;
- For each measure, activity data (actual and projections) must be available to assess the total national abatement potential and associated cost/benefit.

3.3 Assessment of measure interactions and cross-compliance with other pollutants

Individual ammonia abatement measures interact and reduce or increase the abatement potential of other mitigation measures. For example, reducing volatilisation during storage will result in increased total ammoniacal nitrogen (TAN) for landspreading, which could in turn increase these emissions, depending on spreading strategy. In terms of pollution swapping, strategies which reduce emissions from one reactive N loss pathway could lead to an increase in loss via another pathway (N_2O or leached N). Injection of slurry has been shown to decrease ammonia by 70%-90%, but to substantially increase N_2O emissions (Wulf et al. 2002). Similarly, drying manure can reduce ammonia, but substantially increase N_2O (Amon et al. 2006).

A Nitrogen flow inventory approach was taken in assessing the capacity of measures to deliver ammonia abatement. The advantage of this approach was that the additive impacts of measures could be assessed collectively. Costs presented are the *marginal costs per annum* for the quantity of ammonia abated (i.e. The additional costs a farmer will bear for introducing a technique and the associated emissions reduction achieved). Therefore these costs are incurred *in addition* to the current cost for an activity (e.g. buying fertiliser, applying slurry, etc). Costs were estimated as the 'unit cost' of techniques which was defined as the annual additional costs that a farmer incurred as a result of adoption of an abatement measure. This includes the annualised cost of additional capital, repairs, fuel and labour costs and fertiliser N savings.

4. Impact of Food Wise 2025 on ammonia emissions

The increase in agricultural production under the Food Wise 2025 Sustainable Growth Scenario results in total NH_3 emissions of 113.8 kT by 2030 (see Figure 5.1). This represents an 8.9 kT NH_3 increase relative to 1990 and a 6.6 kT NH_3 increase relative to 2005. This increase is principally due to a 16.8 kT NH_3 increase in dairy emissions and 0.7 kT NH_3 increase in pig-sourced emissions by 2030 relative to 2005. In contrast, non-dairy bovine and sheep emissions are projected to decrease by 11.5 and 0.9 kT NH_3 respectively by 2030. Aggregate fertiliser use in 2030 is lower than in 1990. This is not surprising given that usage per hectare has fallen sharply over the last 15 to 20 years, while agricultural production has remained relatively unchanged in volume terms.

However, the overall increase in emissions under SGS is less than proportionate to the increases in agricultural production in these sectors. This is due to the fact that some measures, such as increased animal efficiency, nutrient efficiency and extension of the grazing season are already taken into account in the national inventory. Although fertiliser application increases, it is still 3.8 KT N lower than 1990 levels and marginally lower than 2005 with a diminished proportion being comprised of urea, this results in a lower than expected impact on ammonia emissions.

It should be noted that under the Food Wise 2025 SGS, total methane emissions from enteric fermentation and manure management would increase marginally (4.2%) from 537 gG CH_4 yr^{-1} to 560 gG CH_4 yr^{-1}, although GHG emissions intensity should fall sharply. This is pertinent to the NECD, as there are ongoing discussions around the classification of methane as an air pollutant.

4.1 Refinement of Inventories to reduce emissions

The pressure washing of dairy collection areas in addition to yard scraping, have been found to be effective means of reducing emissions, with a 70% reduction in the emission factor (from 0.75 to 0.225) at a cost of €60 per animal place per annum (Misselbrook et al. 1998). This cost includes the cost of water-use, labour and additional slurry/dirty water to be spread. Also, as the washings were used to dilute slurry, this could further reduce ammonia emissions upon landspreading and provide an environmental and economic co-benefit. As this activity is already carried out by most farmers, it is not considered as a mitigation option *per se* and both the baseline and subsequent emissions reduction targets have recently been recalculated accordingly. While the emissions target would reduce by 2 kT NH_3 (as calculated from 2005 emissions) upon inclusion, this activity would reduce total ammonia emissions by 4.4 kT NH_3 by 2030. This is due to the fact that the growth in dairy-sourced emissions as a proportion of total ammonia emissions will increase substantially up to 2030 (Figure 5.1).

5. Ammonia abatement potential

The cumulative maximum ammonia abatement potential under the Food Wise 2025 SGS was calculated to be 12.05 kT NH_3 by 2030 (Figure 5.1). This maximum abatement assumed a 50% adoption of trailing shoe and represents a 5.1% reduction relative to 2005. If trailing hose is adopted instead, there is a 1 – 1.5 kT NH_3 *reduction* in total abatement. Under the SGS scenario, total emissions would be reduced to a *minimum* of 103.2 kT NH_3, which represents a 3.8% reduction in NH_3 relative to 2005 levels (Figure 5.1). This incorporates inventory modification to include reduced yard emissions which were not previously captured in the inventories (Figure 5.1).

It should be noted that these reductions represent the **maximum biophysical abatement potential** and achieving this level of reductions (for example replacing urea with urease-stabilised urea) could prove extremely challenging in the context of a) incentivising farmer uptake and b) verifying the emissions reduction inside the farm gate (eg. verifying the early spreading of slurry) or the practicality of using the trailing shoe or trailing hose across 50% of the slurry applications. Indeed, significant policy measures would have to be implemented to achieve these levels of uptake. The total costs associated with these reductions are €24.9 million and €35.6 million *per annum* (for SGS with bandspreading and trailing shoe application respectively) by 2030. These costs neither include pricing in labour costs (the farmer’s time) to implement measures, nor the cost of education and advisory services.

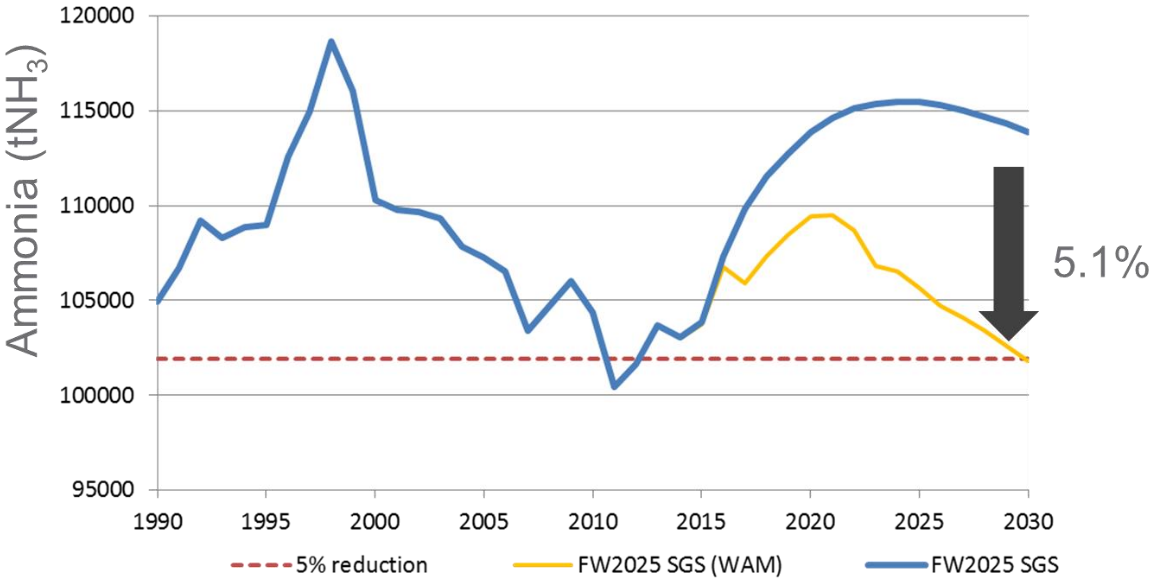

Figure 5.1: Estimated ammonia emissions under Food Wise 2025 Sustainable Growth Scenario without (blue line) and with (gold line) ammonia abatement measures (WAM).

5.1: Ranking of measures and cost-effective ammonia abatement

An examination of the abatement potential and associated costs of individual measures revealed that only the altered slurry timing and possibly crude protein reduction was cost beneficial to the farmer (Figure 5.2). This is in contrast to the GHG MACC analysis previously published by Teagasc, where seven measures were shown to be win-win strategies (Schulte et al. 2012, O'Brien et al. 2014). This is partly due to the fact that some strategies (increased production efficiency per animal, increased N use efficiency, increased grazing) were already incorporated into the SGS scenario. In addition, washing of dairy collection areas (see above) has yet to be incorporated. In the GHG MACC, extended grazing was a key abatement strategy. Within the Food Wise 2025 baseline scenario, the increase of average grazing days from 227 to 248 for dairy cows has already been incorporated**. This extension of the grazing season to 248 days for dairy cows results in a 3.24kT NH_3 reduction in emissions.**

However, the lack of cost-negative strategies for ammonia abatement in comparison to GHG abatement was also due to the more technical nature of interventions required to abate ammonia emissions from housing (as opposed to the control of emissions from animals or soils). Technical interventions to reduce ammonia emissions are dominated by the need for new machinery, chemical amendments and alterations to slurry storage. Similarly, in the GHG MACC analysis, minimum tillage was the only one of six technical measures that was found to be cost-neutral.

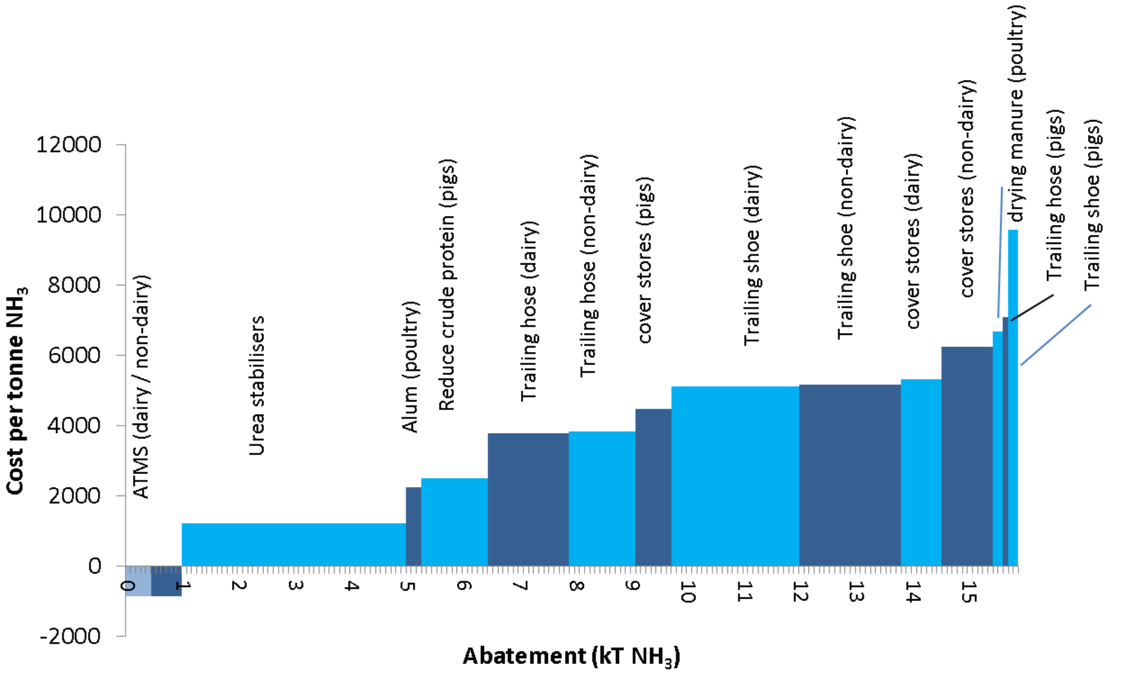

Figure 5.2: Total ammonia abatement and costs associated with individual measures under the Food Wise 2025 Sustainable Growth Scenario

The cumulative abatement and costs are shown in Figure 5.3. Two abatement scenarios are shown: the first (red line) where 50% of pig and bovine slurry is band-spread and the second where 50% is applied by trailing shoe. A maximum abatement potential of **10.6 and 12.0 kT NH_3** is possible under the bandspreading and trailing shoe projections respectively, at a total cost of €24.9 million (bandspread) and €35.6 million per annum (trailing shoe). However, some of the measures (particularly measures associated with pig production) are less cost-effective. If we define *cost effective* ammonia abatement as abatement costs of circa. €5,000 per tonne NH_3-N abated (Reis et al. 2015), then **8 – 9.2 kT NH_3** could be abated at a total cost of €14-€25 million per annum for the bandspreading and trailing shoe scenarios respectively (Figure 5.3). Also when measures are applied in sequence along the entire manure management system, N that is abated cascades down into the subsequent N pool. So, for example, if N is abated during storage, this results in higher available N pools for volatilisation upon landspreading.

A comparison between this analysis and country-specific analysis using the GAINS model shows similar magnitude in terms of the % abatement achievable. The GAINS analysis forecast that a 13 Kt NH_3 abatement for moderate level ambition (MID) and 17 Kt NH_3 abatement for high level ambition (HIGH), with most of this abatement coming from application of fertiliser and manures (13%) with much less from housing (3%), storage (2%) and grazing (1%) (Amann et al. 2011). The associated costs ranged from €14.2 – €45.3 million. The extent and cost of mitigation in our analysis is relatively comparable with a 10.6 - 12 kT NH_3 reduction possible at a cost of €29 - €35.6 million. The main difference between the two sets of analyses is the projected

2020 levels of activity data. **Whilst the GAINS model predicted baseline ammonia emissions to be at 98 kT NH_3 by 2020 (Amann et al. 2007, 2011), our FAPRI analysis predicted the baseline to be 114 kT NH_3.** This discrepancy in levels of forecast activity data may be highly problematic in terms of both the setting and delivery of achievable targets.

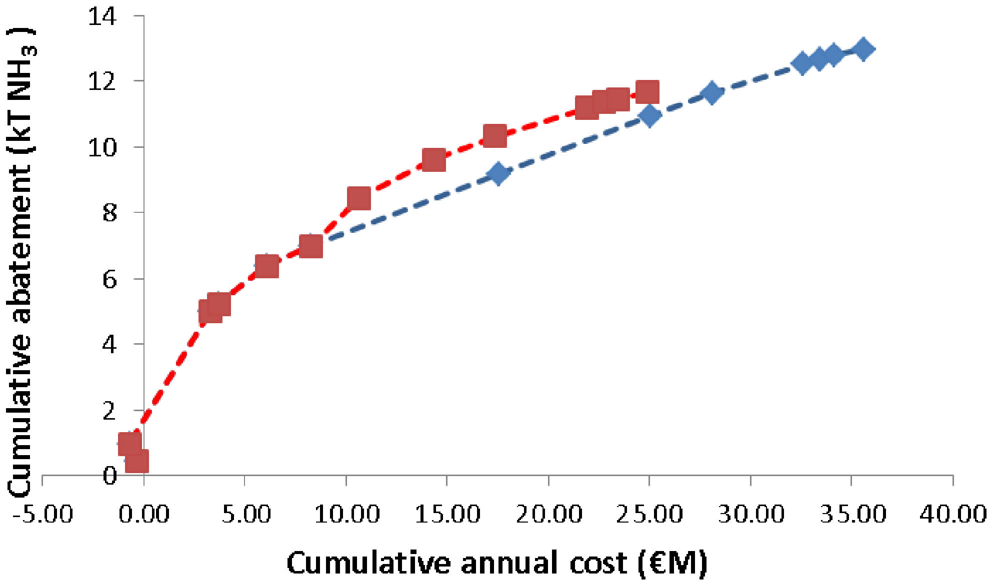

Figure 5.3: Cumulative costs and abatement for the Food Wise 2025 Sustainable Growth Scenario. The blue line indicates abatement with trailing shoe included, whilst the red line includes bandspreading as a landspreading abatement option.

The most cost-effective measures (apart from timing of application) were incorporation of urease inhibitors, the use of trailing hose for bovine slurries, reducing poultry pH with alum amendment and the reduction of crude protein in pig diets. It should also be noted that the costs associated with crude protein supplementation *could* be cost-neutral depending on the relative costs of soy bean meal and supplemental amino acids. These measures accounted for 60% of the mitigation for less than 40% of the total cost. There are some major caveats to the quantification of this mitigation value. First, 100% replacement of urea by urea+urease stabilisers was assumed. This would require financial incentivisation and there are currently only one or two manufacturers, although several fertiliser companies are engaged in product development in this area. Secondly, while these products are on the recommended fertiliser lists, the detection of these compounds in vegetation or animal products is still unknown. Indeed, previous negative publicity surrounding detection of the nitrification inhibitor DCD in New Zealand has made farmers and food companies wary of using some of these compounds. However, the concentration of urease-inhibiting compounds in fertiliser is much lower than for DCD and the product is directly sprayed on the granule, not on the sward. It should also be noted that there is a possibility of urea+urease stabilisers displacing calcium ammonium nitrate (CAN). Indeed, Teagasc and AFBI research has demonstrated that there are substantial benefits in terms of reducing N_2O emissions when urea+urease stabilisers replace CAN (Zaman et al 2013). If this occurred, there could be an increase in ammonia emissions as the emission factor for urea+urease stabilisers is higher than that of CAN. Similarly, a campaign to reduce urea use could result in more farmers using CAN. Other things being equal, a shift to CAN would increase agricultural GHG emissions, as N_2O loss from CAN is 30% higher than for urea.

Reductions in pig crude protein content (4%) reduction should be achievable and also have co-benefits in terms of reducing N_2O and leached N emissions. The abatement value of covering pig stores is highly uncertain as data on the total configuration of outdoor storage was scarce. Alum amendment of poultry litter may also have added benefits for landspreading emissions if the pH effect persists until the litter is applied to land.

It should be noted that three of the four most effective methods in terms of ammonia abatement were also amongst the most expensive: trailing shoe (dairy and non-dairy) and the covering of external bovine slurry stores. Trailing shoe is more effective at reducing emissions than trailing hose. However, increases in nitrogen fertiliser replacement value are not enough to offset the increased costs, which were calculated for contractor spreading. The use of trailing shoe could be made more cost-efficient by targeting spreading using this technique to summer months. An analysis has previously shown that May to August are the most high risk months for ammonia emissions in Ireland (Lalor & Lanigan 2010). Targeting abatement to this period would reduce abatement from 3.3 kT NH_3 to 1.8 kT NH_3, whilst reducing costs from €8.7 million to €4 million.

Finally, it should be noted that the cost of advice and education for farmers and the cost of farmers' time (which is particularly important for part-time farmers working off the farm) has not been factored into this analysis.

6. Individual Measures

6.1 Landspreading measures

The landspreading measures comprise a number of related farm management actions that will reduce the ammonia emissions associated with slurry spreading. These include: a continued transition from summer application to spring application of manure (using splashplate application) and use of low-emission application methods for both cattle and pig slurry. This measure interacts with the measure "extended grazing", since an extension of the grazing season will reduce the amount of manure stored, and hence the activity data to which the measure "manure management" applies. The reference technique currently in use is splashplate or broadcast application of slurry, where untreated slurry or solid manure is spread over the whole soil surface. The emission factor for summer application is 48% of total ammoniacal nitrogen (TAN).

6.1.1 Altered Timing Management System (ATMS): Spring application

Reduced ammonia emissions following landspreading occur when weather conditions at the time favour a reduction in NH_3 losses. Altered timing should also reduce the N_2O emissions associated with redeposition. These reduced NH_3 losses also increases the fertilizer replacement economic value of slurry. This measure is primarily effective with cattle slurry which has a higher dry matter (and hence emission factor) than pig slurry. The measure can also be extended to altered time of day application (ie. Evening spreading) as there is evidence that this can reduce emissions by 20% (Dowling et al. 2008). The main challenge associated with this measure is verification of targeted spreading and the generation of activity data for inclusion in national inventories.

Constraints: The principal biophysical constraint is soil trafficability, with 33% of soils defined as poorly drained and potentially unsuited to altered timing of application. As a result, the opportunity to spread in early spring is severely limited on these soils (Lalor & Lanigan 2010, Lalor et al. 2011).

Cross-compliance: Early spreading has been shown to also reduce N_2O emissions (Bourdin et al. 2014). However, an increased risk of leaching or run-off may occur during these periods.

6.1.2 Bandspreader or trailing shoe application methods

These application techniques reduce ammonia losses and also increase the fertilizer replacement economic value (NFRV) of slurry, and therefore reduce the total fertilizer N inputs and reduce associated reactive N emissions from soil. This occurs by reducing the surface area exposed for volatilisation. Trailing shoe is more effective at reducing volatilisation, as the slurry is placed directly on the soil beneath the sward. Some studies have suggested that this practice leads to increases in N_2O emissions, but Irish studies (Meade et al. 2010; Bourdin et al. 2014) on bandspreading and trailing shoe application to pasture and arable land have not detected any significant increase. It should be noted that there was no statistical difference in the emissions associated with splashplate application of slurry in comparison with trailing shoe/trailing hose application during spring and late autumn in Irish studies, with observed reduction in volatilisation of 60% (summer) and 13% (spring, not significant) compared to splashplate application (Dowling et al. 2010, Bourdin et al. 2014). Similarly, bandspreading was observed to reduce emissions by 40% (summer) and 10% (spring, not significant). Therefore a shift of slurry application to spring will, *per se*, reduce the efficacy of alternative techniques compared to trailing shoe in terms of the total amount of NH_3 abated when techniques are used in combination.

Less cost-effective abatement potential was observed for band-spread and trailing shoe applied pig slurry. This was due to the fact that emissions for the reference technique (splash-plate) were much lower than for cattle slurry because the lower dry matter content of pig slurry results in faster infiltration of slurry into the soil.

Constraints: A 50% limit on the slurry applied by alternative techniques was assumed as agricultural contractors are estimated to account for approximately 50% of slurry spread in Ireland (Hennessy et al., 2011). This constraint was assumed due to the high cost of the technology, which will primarily restrict adoption to agricultural contractors. In essence, the volume of slurry applied annually with each machine has a large effect on the gross cost of ammonia abatement. Farmer-owned machines will typically spread 500 – 2000 m^3 yr^{-1} slurry, while contractors will spread 5000 – 20000 m^3 yr^{-1} slurry (Lalor 2011). As a result, the marginal abatement costs will increase approximately ten-fold for farmer-owned machines. Conversely, if 100% of slurry was spread by bandspreading or trailing shoe, the amount of NH_3 abated would be 4.1 and 6.2 kT NH_3 respectively (double the abatement at 50% spreading rate). However, the costs would increase from €4.55 and €6.21 per kg NH_3 abated (for trailing hose and trailing shoe respectively) to €21 and €27 per kg NH_3 abated, as individual farmers would have to buy their own machines.

6.2 Housing and storage measures

There are few mitigation measures for cattle housing applicable to Ireland. This arises because the normal method of cattle housing is either in slatted sheds over slatted tanks, in cubicle sheds with floors scraped daily into open tanks or on straw bedding. In addition, there is little data on any of the (category 1 or 2) mitigation strategies discussed in the ammonia Guidance Document (WGSR 49 Informal document No 21). However, DAFM are currently funding Teagasc, UCD and AFBI to carry out a large project (Low-Ammo) that is tasked with assessment of housing and storage ammonia emissions and associated mitigation techniques. Some of the low cost techniques, such as insulation of houses to prevent increased temperatures are not applicable to Ireland as animals are outdoors during these periods. Similarly, the use of extended grazing is already accounted for in the FoodWise 2025 SGS scenario. As discussed earlier, the extension of the average number of grazing days from 227 to 248 days will deliver 3.7 kT NH_3 that would otherwise be added to both of the FW2025 scenarios.

With respect to pig and poultry systems, air scrubbers for forced ventilation systems were not considered due to the high cost (€15,000 per t N abated) and dust loading issues in poultry systems. Nor was consideration given to acidification for pig or cattle slurry due to the need to refit storage tanks in all housing systems.

The following abatement techniques were assessed:

6.2.1. Covering outdoor storage

Covers include tight lids, floating covers and LECA balls.

Tight lids: This is the most effective measure to reduce emissions from slurry stored in tanks or silos. These covers are well sealed to minimize air exchange, but are costly and the ability to retrofit onto existing external storage depends on whether they can be modified to accept the extra load.

Floating covers: floating cover sheeting may be a type of plastic, canvas, geotextile or other suitable material. It is ideal for small earth banked lagoons or tanks that cannot take the structural load of tight lids. However, they are difficult to implement on tanks, especially those with high sides.

LECA covers can be easily applied to non-crusting pig manure or more dilute dairy slurry.

Crusting of slurries (where a crust is allowed to form on top of the open slurry tanks for the entire storage period), and a crust to form on the indoor tanks when animals are turned out to pasture and to spread was not considered as, in practice both of these opportunities are fully used.

The abatement potential of these covers ranged from 40%-80%. A mean value of 60% was set for cattle slurry in open stores and 60% for pig slurry. LECA balls were assumed to be used as the cover for pig slurry and floating covers (with a small proportion of tight covers) for cattle slurry. The costs were €3 per m^3 for covering pig stores and €1.50 per m^3 for cattle stores.

Constraints: All open pig and cattle slurry stores were covered. This equated to 20% of pig and 31% of cattle slurry stored.

Cross-compliance: Increased TAN in slurry will improve nitrogen fertiliser replacement value, but unless applied to fields appropriately may simply lead to higher ammonia emissions upon land-spreading.

6.2.2. Aerated open manure storage under cages to dry manure

Ammonia emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit. This was applied to all poultry houses at a cost of €4 per kg N abated.

Cross-compliance: Increased TAN in litter can be lost upon application to land.

6.2.3 Amendment of poultry litter with alum

Applications of aluminium sulphate ($Al_2(SO_4)_3.14H_2O$), commonly referred to as alum, to poultry litter have been shown to decrease P runoff from lands fertilized with litter and to inhibit NH_3 volatilization (Meisinger et al. 2001, Fenton et al. 2011). Alum will reduce ammonia emissions from the houses, both by reducing its production in the litter and by reducing ventilation needs. The total reduction has been estimated to be between 60-70% (Moore et al. 2000, Meisinger et al. 2001). The reduction in pH may also persist during landspreading of litter, further reducing ammonia loss.

Cross-compliance: Amendment of manures with alum has also been shown to reduce P loss (Fenton et al. 2011). The reduction in litter pH following application may also causes pathogen numbers to decrease (Moore et al. 2000).

6.3 Feeding Strategies

These strategies have the advantage that they can reduce emissions from both storage and upon application to the land. Reducing crude protein (CP) content can reduce both N excreted and the proportion of N in urine and lead to a reduction in ammonia and N_2O emissions (Lynch et al. 2008, Meade et al. 2011). Lowering crude protein in pastoral systems is difficult. In beef systems, the scope was considered to be small for two reasons. Firstly, most cattle are managed extensively with low levels of supplementation, so dietary manipulation to reduce CP is limited. Secondly, the level of N application is very low, approximately 40 kg per hectare annually, so the capacity to reduce N fertilizer (in order to reduce CP) is also limited. Only a minority of cattle are finished on high concentrate indoor systems and in these instances, CP levels are already low (<12%). It might be argued that CP in concentrate for weanling/store cattle (i.e. young, growing animals) could be reduced slightly (typically rations are ~14-16%) but given the highly variable nature of grass silage quality, the higher levels than those that are strictly necessary are justified.

As a result, the analysis of the impact of crude protein was restricted to pigs.

7.3.1 Reducing Crude Protein content in pigs

A fourthree percent reduction in crude protein diets was assumed, with a 10% reduction per 1% CP reduction assumed. The cost of the diet manipulations was assumed in the range of €-10 to €10 per 1000 kg of feed, depending on market conditions for feed ingredients and the cost of the synthetic amino acids.

Constraints: Reductions in crude protein were applied for all pig systems.

Cross compliance: This strategy will result in reduced N_2O and ammonia emissions. Decreased dietary CP content can also lessen manure volume produced per animal due to lower water consumption and reduced manure total ammoniacal N (TAN) content. A 7% reduction in CP has previously been shown to decrease ammonia and N_2O by 12% upon the landspreading of slurry derived from these diets (Meade at al. 2011).

6.4: Fertilisers

Ammonia emissions associated with fertilizer applications are dependent on fertilizer type, weather and soil conditions. Emissions from urea-based fertilizers are much greater than from ammonium or nitrate fertilisers because rapid hydrolysis of urea will cause localised increases in pH. Abatement of volatilisation can occur either by optimising timing of application or the use of urease stabilisers. Urease inhibitors delay the conversion of urea to ammonium carbonate by directly inhibiting the action of the enzyme urease. This delayed/slower hydrolysis is associated with a much smaller increase in pH around the urea prill and, consequently, a significantly lower ammonia emission. This analysis assumed a 70% reduction in volatilisation and a net cost of €0.26 per kg N applied (Chadwick et al., 2005; Watson et al., 1994). The cost reflected the difference between urea (at €0.86 per kgN) and a commercially available urease stabiliser-coated urea product (€1.12 per kgN).

Table 6.1: Percentage and total NH_3 abatement, associated marginal costs and literature reference for ammonia abatement strategies inputted into the MACC analysis

Measure	% reduction	Total Reductions (kT NH_3)	Cost per tonne N abated	Reference
Altered Timing Management System (ATMS)	20%	0.96	Saving in fertiliser N (x 0.86 per kg N)	Reis et al. 2015
Trailing Hose (Bandspreading)	40% (summer) 10% (other times)	2.76	€0.68 per m^3 slurry	Bourdin et al. 2013
Trailing Shoe	60% (summer) 13% (other times)	4.09	€1.28 per m^3 slurry	Dowling et al. 2008 Dowling 2012
Alum amendment	70%	0.19	€0.09 per unit	Meisinger et al. 2001
Cover storage units	60%	2.17	€3 per m^3 slurry (pigs) €1.50 per m^3 slurry (bovines)	Reis et al. 2015
Reduce Crude Protein (pigs only)	10% per 1% reduction in CP	1.11	-€10 - €10 per tonne feed	Meade et al. 2011
Drying manure (poultry)	60%	0.15	€6 per kgN abated	Reis et al. 2015
Urea stabilisers	70%	4.03	€0.26 extra per kg N	Reis et al. 2015

7. Future strategies and requirements

This analysis does not provide an exhaustive analysis of all ammonia abatement strategies. Considerable research is currently being undertaken on the assessment of housing and storage strategies for ammonia abatement. The potential mitigation figures quoted above may alter into the future and we envisage the need for another iteration of this analysis prior to 2030. This due to a) new technologies that will come on-stream, b) changes in emission factors currently being proposed by the Task Force on Emissions Inventories and Projections (TFEIP) and c) proposed new emission sources from industry that will lessen agricultures share of total ammonia emissions.

7.1 Housing and Storage

While housing abatement for bovine systems will remain challenging, future expansion of the pig and poultry sector will necessitate the construction of low emission housing units. This will provide an opportunity for the incorporation of air scrubbers and biotrickling filters to remove ammonia from exhaust air as this is the most cost-effective way for uptake of these technologies. In addition, new facilities arising from expansion will also offer the opportunity for incorporation of external storage and/or re-inforced storage which would allow for the use of acidification, which has been shown to be extremely effective at reducing emissions during storage (Petersen et al. 2012).

Chemical amendments in both slurry and solid manure systems may be included in the future. Previous studies have shown that alum, polyaluminium chloride and ferric chloride have been very effective at reducing ammonia emissions during storage and landspreading (O'Flynn et al. 2013, Brennan et al. 2015). The use of zeolite and other ammonia adsorbents may also provide a viable reduction strategy.

Requirements: The last farm facilities survey was in 2003 (Hyde & Carton 2003). There is an urgent need for more activity data regarding the type and configuration of housing and storage in Ireland, in order to provide more accurate analysis in the future and to tailor abatement strategies. Consideration could be given to funding a farm facilities study which could parallel the Teagasc National Farm Survey. Such an approach would greatly enhance the policy usefulness of the farm facilities data gathered and would also be a more accurate means to aggregate estimates of national level abatement potential and associated costs. There is a particular need to investigate pig and poultry mitigation strategies.

7.2 Landspreading

Amendment of slurry will offer further reductions in ammonia emissions. This will include the use of urease stabilisers (McGeough et al. 2014) and other amendments (Brennan et al. 2015).

Almost all solid manure in Ireland is spread on grassland, in the autumn, to avoid grass spoilage. There are no mitigation measures available- most grassland in Ireland is permanent pasture and ploughing is unlikely in the autumn. As a result, abatement strategies involving the incorporation of manures soon after application on arable soils would make very marginal differences. However, increases in arable area envisaged under either of the FW2025 scenarios may result in greater use of organic manure and increase the impact of these abatement strategies.

Requirements: There is a requirement to generate abatement strategies for straw-based systems and the use of solid manures.

7.3 Optimising Farm N Balance

Improving farm N balances offers a win-win scenario in terms of reducing all reactive N emissions. Nitrogen management is based on the premise that decreasing the nitrogen surplus and increasing nitrogen use efficiency contribute to abatement of ammonia emissions. Improvements in fertiliser timing, precision application and new fertiliser products, allied to greater recycling of nutrients on farm could lead to a greater retention of ammonium N.

The development of new slow-release and urease inhibiting fertiliser products will also offer a strategy to reduce reactive N emissions.

8. Conclusions

Ammonia (NH_3) emissions during the landspreading of cattle and pig slurry represent a source of both considerable loss of nitrogen and significant atmospheric pollution. By 2030 the maximum technical potential to abate ammonia is between 10.6 and 12 kT NH_3 at a cost of between €24.9 and €35.6 million for the Food Wise 2025 Sustainable Growth Scenario. This represents the maximum achievable potential, with 8 – 9.2 kT NH_3 abatement more likely in terms of cost effectiveness. Altered slurry spreading and crude protein diets in pigs may offer cost neutral strategies, whilst urea substitution, chemical amendment, trailing hose/trailing shoe offer the most abatement (but not always cost) effective strategies in terms of total abatement potential. Housing and storage abatement, particularly in the pig sector were the least cost-beneficial. When adopting strategies, particularly in terms of fertiliser and landspreading techniques, there is a risk that higher N_2O emissions may result from ammonia abatement. The combined impact of measures of total reactive N losses should subsequently be assessed.

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