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Assessment of the Impact of Ammonia Emissions from Intensive Agriculture Installations on Special Areas of Conservation and Special Protection Areas

Authors: David B. Kelleghan, Enda T. Hayes, Mark Everard and Thomas P. Curran

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

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- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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Assessment of the Impact of Ammonia Emissions from Intensive Agriculture Installations on Special Areas of Conservation and Special Protection Areas

(2013-EH-MS-14)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Dublin and the University of the West of England

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DISCLAIMER

This report is based on research carried out/data from 2014 to 2018. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Agriculture is responsible for the production of *c*.98% of atmospheric ammonia emissions in Ireland, of which 4% and 3% were from the rearing of pigs and poultry, respectively, in 2016. Manure produced by both pigs and poultry also contributes to the emission category "manure fertiliser", which accounts for 30% of national emissions (predominantly from cattle). Because of the intensive nature of pig and poultry production, their contributions may have a higher impact on a local level, acting as concentrated point sources of atmospheric ammonia. The acidification and eutrophication of ecosystems caused by the deposition of atmospheric ammonia is of consequence to all habitats, but more so to sensitive habitats and species, such as heaths, bogs and calcareous grasslands. In Ireland, a large proportion of such habitats is designated as part of the Natura 2000 network, which includes Special Areas of Conservation and Special Protection Areas. These sites are protected at the European level, under both the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC), creating a comprehensive network of protected sites for wild species and habitats. Additionally, atmospheric ammonia emissions contribute to particulate matter formation, which can have an impact on human health, with recent research highlighting that ammonia concentrations may also be problematic. When considering impacts from an intensive agriculture unit it is important to first understand how much ammonia is produced by that unit and how far it spreads in the atmosphere. The AmmoniaN2K project intended to meet both these points, in addition to other objectives, namely:

1. Use advanced monitoring equipment to monitor ammonia emissions over extended periods of time on four case study farms (one broiler, one layer and two pig farms).
2. Model the dispersion and deposition of atmospheric ammonia of these farms.
3. Identify a representative proportion of farms below the Industrial Emission Directive (IED) threshold/ unlicensed farms, allowing for the identification of areas at risk from cumulative impacts.
4. Create a risk-based atmospheric concentration model incorporating IED-licensed pig and poultry farms, in combination with other ammonia sources, to identify Natura 2000 sites at risk from impacts.
5. Monitor atmospheric ammonia concentrations in a sample of Irish Natura 2000 sites.

Monitoring of emissions undertaken by this project aimed to ascertain current emission rates from pig and poultry houses in Ireland, potentially informing the use of such rates by the Environmental Protection Agency (EPA) and other agencies. Simple Calculation of Atmospheric Impact Limits (SCAIL-Agriculture) provides emission and ventilation factors per animal, which can be incorporated into a free-to-use online model that predicts the impact of pig, poultry or cattle houses on Natura 2000 sites. Monitored emission rates from four farms were compared with rates currently provided in EPA Annual Environmental Report/Pollutant Release and Transfer Register (AER/PRTR) guidance and those in the SCAIL-Agriculture report. When modelling the impact on ecosystems as part of the Habitats Directive (92/43/EEC), the precautionary principle should be applied and, unless more detailed site-specific information is available, the highest relevant emission factor should be used. This study recorded detailed emission rates representative of both seasonal and diurnal variation. When averaged, these emission rates were 0.04 kg NH_3 bird^{-1} year^{-1} for broilers, 0.09 kg NH_3 bird^{-1} year^{-1} for layers, 4.46–5.58 kg NH_3 animal^{-1} year^{-1} for dry/pregnant sows, 6.57–6.61 kg NH_3 animal^{-1} day^{-1} for farrowing sows, 0.7–1.14 kg NH_3 animal^{-1} year^{-1} for weaners and 2.0–3.99 kg NH_3 animal^{-1} year^{-1} for finishing pigs. The rate presented for broilers presumes 231 production days a year, as, unlike pig and layer production, broiler production does not occur 365 days a year. This is an important consideration if modelling is carried out using emission rates presented as a daily rate, such as in the EPA AER/PRTR guidance. As impacts on habitats are assessed based on exceedance of annual average concentration and deposition rates, the annual average emission rate should be used when modelling the dispersion of ammonia from such farms.

Atmospheric dispersion modelling using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) allowed comparable dispersion models to be produced for the monitored pig and poultry farms. Modelled concentrations downwind of monitored farms potentially exceed concentrations similar to those observed on Moninea Bog in Northern Ireland, where severe negative ecological effects were observed, within 146, 129 and 581 m of Broiler Farm, Layer Farm and Pig Farm 2, respectively. The critical level for higher plants was exceeded from contributions of the farms alone and occurred within 432, 399, 800 and 1685 m of Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively. The lower critical level for bryophytes and lichens was exceeded within 187, 172, 389 and 1685 m of Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively. Published guidance from the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) has highlighted the de minimis value for project contributions to dry deposition of nitrogen at 0.3 $kg\,N\,ha^{-1}\,year^{-1}$. Dispersion modelling by this project indicates distance ranges of 3–10, 3–7, 6–10 and 13–20 km as maximum distances downwind potentially in receipt of 0.3 $kg\,N\,ha^{-1}\,year^{-1}$ from the Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively. The distance from the farms where these concentrations are exceeded could be influenced by including outdoor manure storage in dispersion models and the potential occurrence of other hotspot sources of ammonia nearby. This has shown that, for these farms, a 10 km screening threshold may be appropriate for the protection of Natura 2000 sites from potential impacts of atmospheric ammonia. However, the largest farm monitored had a much greater dispersion extent where de minimis contributions extended to 20 km.

Because of the nature of ammonia emissions from intensive point sources, it is important that farms with bird and animal numbers below EPA licensing limits are also considered. An unlicensed farm close to a Natura 2000 site could potentially have a higher impact than a large licensed farm further away. This project identified an additional 760 potentially below-threshold intensive agriculture houses in Ireland, though work conducted did not clarify if houses were stocked at the time and did not distinguish the type further than pig and poultry (i.e. the work did not identify if buildings on farms were breeder, layer, broiler, duck, turkey, finisher, weaner, etc.). The contribution of pig and poultry farms to the impact on Natura 2000 sites needs to be considered in combination with ambient concentrations from Ireland's extensive, growing dairy industry in addition to slurry spreading. As such, Mapping Ammonia Risk on Sensitive Habitats (MARSH) modelling conducted by this project considered all publicly available sources of atmospheric ammonia in Ireland. This highlighted that *c.*81% of Natura 2000 sites may exceed a concentration of 1 $\mu g\,NH_3\,m^{-3}$, at which impacts occur on lichen and moss species. Additionally, 6% of Natura 2000 sites may potentially exceed a concentration of 3 $\mu g\,NH_3\,m^{-3}$, at which impacts are expected on higher plants. Further modelling is likely to be required to address the cumulative impacts from multiple hotspot sources of ammonia, as dispersion modelling has indicated concentrations higher than those produced by the national risk map.

The AmmoniaN2K project has identified a number of gaps currently limiting Ireland's ability to adequately comply with European directives. These gaps should be filled by, among other approaches discussed in this report, the following:

- a detailed source-apportioned ammonia concentration map including all sub-IED threshold pig and poultry farms and recent agricultural data;
- a continuous ammonia concentration monitoring network;
- further monitoring of both concentrations and impacts on Natura 2000 sites;
- extensive monitoring of hotspot sources to clarify the contribution of size to concentration and dispersion extent;
- a publicly available database of critical level and load criteria for qualifying features on Natura 2000 sites;
- a strategy for assessing impacts of slurry spreading and grazing on Natura 2000 sites;
- guidance to ensure that existing tools (i.e. SCAIL-Agriculture) are used correctly in an Irish context.

1 Introduction

Ireland has a strong tradition of agricultural production; however, agriculture is the primary source of ammonia emissions globally. As an EU Member State, Ireland must comply with a number of EU directives that require the protection of sensitive habitats and the reduction of ammonia emissions. Reported emissions for Ireland in 2016, 2017 and 2018 exceeded the limit set for ammonia, and without additional abatement techniques these are predicted to continue increasing on account of expanding livestock numbers under Food Wise 2025. Though intensive agriculture units contribute a small proportion of Ireland's total emissions (7% in 2016), international research indicates concentrations near these facilities are likely to cause ecological impacts (Sutton *et al*., 2011; Tang *et al*., 2018). This report investigates the sources, concentrations, deposition rates and emission rates of atmospheric ammonia, with a view to identifying gaps in Ireland's ability to assess and protect against resulting negative ecological effects.

The contribution of agriculture to Ireland's gross domestic product reached an all-time high of €684 million in the third quarter of 2017 (Trading Economics, 2018). Across Europe, agriculture accounts for between 80% and 100% of each Member State's atmospheric ammonia emissions, whereas in Ireland it accounts for 98% (European Environment Agency, 2017). Cattle farming in the form of beef and dairying represents *c*.51% of these emissions (European Environment Agency, 2017), which in Ireland is primarily carried out on grassland systems (Hyde *et al*., 2003). This excludes emissions from the spreading of animal manure, which consists of cattle, pig and poultry manure (30% of national total). The primary source of ammonia is through the volatilisation of animal waste, but it can also occur from burning biomass and fossil fuels (Olivier *et al*., 1998). Ammonia is produced by the vaporisation of urea, uric acid and undigested proteins (Behera *et al*., 2013). Cattle and pigs excrete unused nitrogen in urine as urea and undigested proteins in faeces, whereas in poultry both uric acid and undigested proteins are excreted in their faeces. Water and oxygen must be present in order for ammonia to be produced and its production is further enhanced by temperature and pH, when it is formed alongside carbon dioxide (CO_2) (Groot Koerkamp *et al*., 1998a).

Ireland was one of five EU Member States to have exceeded their threshold for ammonia in 2016, with the others being Austria, Croatia, Germany and Spain. Though ammonia emissions are increasing across all of Europe, the highest increases at the time were exhibited in Ireland, the UK and Italy (European Environment Agency, 2018). The Environmental Protection Agency (EPA) has identified Ireland's exceedance as being largely due to the increasing cattle population under Food Wise 2025 (EPA, 2018a). The main instruments that have been used by the EU to limit ammonia emissions directly are the National Emission Ceilings (NEC) Directive (2016/2284/EU) and the Gothenburg Protocol (United Nations Economic Commission for Europe, 2007). Ireland's emission ceiling set by the NEC Directive for ammonia is currently 116 kilotonnes, which was exceeded for the first time in 2016 (EPA, 2018a). Since 2011, Ireland's ammonia emissions have been continuously increasing and under the recently updated NEC Directive Ireland is required to reduce ammonia emissions by 1% in 2020 and by 5% by 2030 (based on a 2005 baseline) (EPA, 2016a). Considering that Ireland aims to continue the expansion of agri-food production under Food Wise 2025 (DAFM, 2015), continued increases in agricultural production will lead to increases in ammonia emissions (Stoate *et al*., 2009). Teagasc predicts an emission range between 123.87 and 137.82 kt, under six different scenarios without the consideration of mitigation measures. Even when the maximum mitigation potential of 24.11 kt is considered, Ireland is still predicted to exceed the 2030 emissions ceiling (see Figure 1.1) (Donnellan *et al*., 2018). The new emissions ceilings of 112.1 kt by 2020 and 107.5 kt by 2030 are going to be extremely difficult for Ireland to meet. Ireland produced a "National Air Pollution Control Programme" (NAPCP) (Department of Communications, Climate Action and Environment, 2019), which closed for consultation on 5 July 2019. The NAPCP paired with the "Code of Good Agricultural Practice for Reducing Ammonia

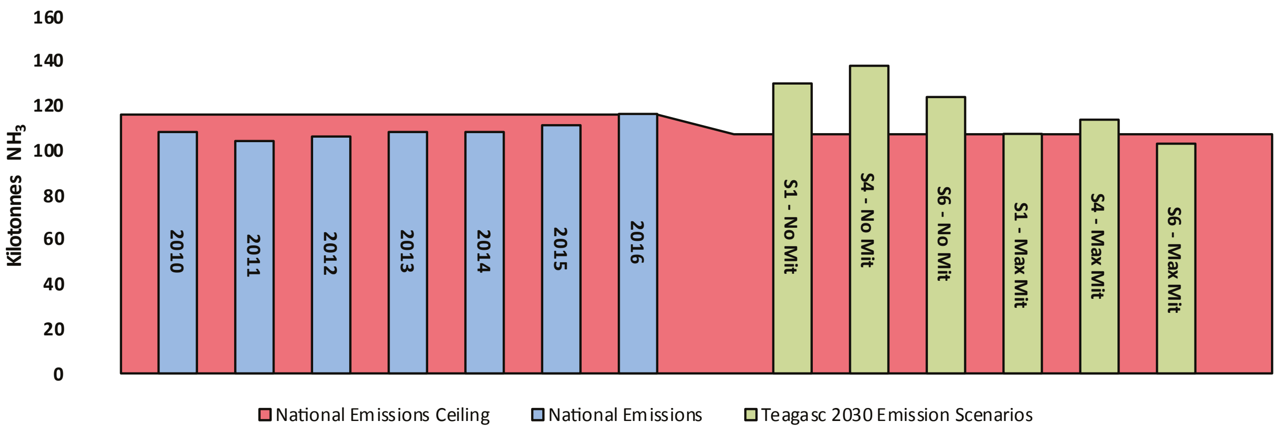

Figure 1.1. Historic (EPA, 2018b) and predicted (Donnellan *et al*., 2018) national ammonia emission rates for Ireland, against the NEC Directive limit. Teagasc 2030 emission scenarios are representative of scenarios 1, 4 and 6, both with and without maximum mitigation measures.

Emissions from Agriculture" (DAFM, 2019), which closed for consultation on 21 June 2019, outlines a number of approaches vital to reducing national emissions and concentrations of ammonia.

The 2018 Teagasc report *Future Scenarios for Irish Agriculture: Implications for Greenhouse Gas and Ammonia Emissions* (Donnellan *et al*., 2018) identified six scenarios (S1–6) for emissions in 2030, for which the influence of maximum emission reductions was modelled for three of the scenarios – S1 (moderate decrease in suckler cows), S4 (modest decrease in suckler and stronger increase in dairy) and S6 (strong decrease in suckler and stronger increase in dairy). Predicted emission scenarios highlight that Ireland can only meet its targets if maximum mitigation measures are implemented, which presumes a linear uptake in mitigation measures across all farms. This occurs in both S1 and S6, with a greater reduction in S6 on account of the strong decrease in the suckler herd. Additionally, the updated NEC Directive requires every Member State to set up a mandatory National Ecosystem Monitoring Network (NEMN), intended to represent ecosystem health in relation to air pollution (primarily concentration and deposition), with sites selected using a risk-based approach. Increasing ammonia emissions limit Ireland's ability to comply with not only the targets set by the NEC Directive but also the EU Habitats Directive (92/43/EEC) (EU, 1992) because of ecological impacts associated with high concentrations of ammonia. Although these scenarios are predominantly determined by cattle management, the NEMN specifically requires sensitive sites to not exceed harmful concentrations; this is important when considering contribution from hotspot sources of ammonia. In the UK, the areas with a high number of hotspot sources of ammonia had the highest ambient concentrations (Tang *et al*., 2018).

Emissions data for every EU Member State are submitted annually to the European Environment Agency in compliance with the Convention on Long-range Transboundary Air Pollution (CLRTAP). Irish ammonia emissions for 2016 are shown in Figure 1.2a, of which 51% is attributable to cattle. Manure fertiliser refers to emissions from manure produced by all animals, including pig and poultry. However, because of the dominance of emissions from cattle compared with pigs (4%) and poultry (3%), the majority of this 30% is probably attributable to cattle. The 1999 inventory, which categorised land spreading as part of each sector's source, identified 78% of total agricultural emissions to have arisen from cattle, with pigs at 8% and poultry at 4% (Figure 1.2b). These increases are the result of the incorporation of manure produced from each sector, seeing an additional 27%, 4% and 1% assigned to cattle, pigs and poultry, respectively. The difference between these three sources is equivalent to 32%, roughly proportional to the 30% contribution of manure fertiliser shown in Figure 1.2a. This approximation increases the contribution of pigs and poultry to national emissions to 8% and 4% (12% in total), respectively, when manure spreading is considered in combination with rearing.

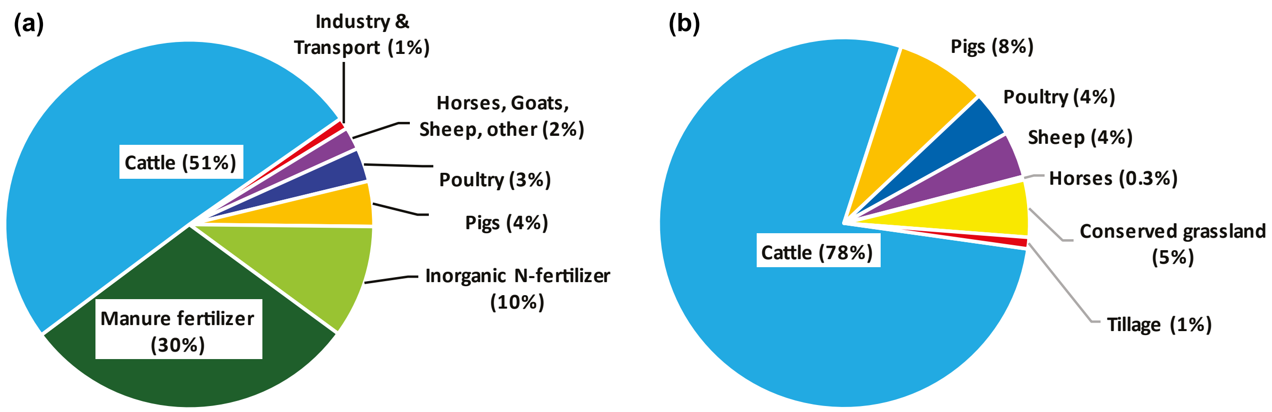

Figure 1.2. (a) Irish ammonia emissions per sector for 2016, rounded to the nearest per cent (European Environment Agency, 2017). (b) Proportion of emissions identified in 1999 (Hyde *et al.*, 2003).

1.1 National Clean Air Strategy

The revised NEC Directive sets out a template intended to assist Member States with the establishment of national codes of agricultural good practice to reduce ammonia emissions. The Irish Clean Air Strategy report *Cleaning Our Air* highlights that emission reductions in Ireland can be best achieved by switching from standard "splash-plate" slurry spreading to trailing shoe, covering manure stores and using urea stabilisers in fertilisers (Department of Communications, Climate Action and Environment, 2017). *Cleaning Our Air* highlights the difficulty identified by Teagasc in reducing emissions from housing because of the storage of slurry below the animals. This applies directly to any potential emission reduction from pig and poultry farms, where in both broiler and traditional pig farming manure is stored in house with the animals. An exception is in modern layer production houses, where manure can be dried below enriched cages and removed using conveyor belts (e.g. Alberdi *et al.*, 2016), allowing for greater control of emissions.

The UK published its Clean Air Strategy in January 2019, in which it outlined a number of measures designed specifically to reduce ammonia emissions, concentrations and associated health and ecological impacts. The primary goal of these actions is to reduce ammonia concentrations on sensitive sites by 17% by 2030, and monitoring will be conducted on this. The UK government plans to support farmers who invest in emission reduction technology, as its adoption will become a necessity, as part of the development of an overarching code of good practice to reduce ammonia emissions. The UK government also intends to further regulate fertiliser use and extend environmental permitting to include cattle farming (Department for Environment Food & Rural Affairs, 2019). All these measures – if acted upon – should substantially reduce the UK's emissions; Ireland may need to consider adopting all approaches in order to reach its 2030 ceiling.

1.2 Intensive Agriculture in Ireland

Intensive agricultural production in Ireland applies primarily to pig and poultry farming, with farms both above and below the Industrial Emissions Directive (IED) (2010/75/EU) (EU, 2010) licensing threshold. Food Wise 2025 aims to increase efficiency and productivity of all agricultural sectors, including pigs and poultry (DAFM, 2015). A study analysing long-term trends in ammonia concentrations across the UK identified that areas with higher production of pigs and poultry exhibited the highest concentrations (as high as 22 µg NH_3 m^{-3}) (Tang *et al.*, 2018). As of spring 2019, there are 120 pig units and 106 poultry units that operate under an IED licence granted by the EPA, i.e. facilities with a capacity greater than (1) 40,000 birds; (2) 2000 production pigs (over 30 kg); or (3) 750 sows. These sites must report their annual releases (emissions) under Statutory Instrument (S.I.) 123 of 2007 and S.I. 649 of 2011 – the Pollutant Release and Transfer Register (PRTR) Regulations – and submit an Annual Environmental Report (AER) to the EPA (EPA, 2016b). An inventory of licensed houses is publicly available through the EPA, whereas the locations of farms that fall below this threshold are currently unavailable. The emissions of greenhouse gases and ammonia from licensed farms are calculated annually as part of an AER.

The most recently available count of poultry in Ireland is from the Central Statistics Office 2010 agricultural survey (CSO, 2010), which recorded 10,924,800 birds in Ireland. More recent data have been measured for pig production, and 1,556,900 pigs were counted in 2017 (CSO, 2018). Pig and poultry numbers increased by 50% during the 1990s (Hyde *et al*., 2003). The primary production of the poultry industry is currently valued at €142 million, whereas that of pigs is valued at €467.6 million (DAFM, 2017).

The Irish emissions inventory divides poultry into layers, broilers and other poultry. Layers are presumed to be housed in cages and all other types in litter-based systems. Pigs in Ireland are housed throughout the year, primarily in slatted houses (Hyde *et al*., 2003). The 2003 inventory of ammonia emissions in Ireland estimated the contribution of housing, storage and land spreading of manure from all sectors to national emissions (Hyde *et al*., 2003).

Figure 1.3 shows the estimated contribution for pig (Figure 1.3a) and poultry (Figure 1.3b) production to their total emissions, with housing the largest source for both sectors. Land spreading contributed 45% of ammonia emissions for pigs, but only 28% for poultry. This is probably on account of the end use of manure; poultry manure can often be used in mushroom production (Miller and Macauley, 1988), whereas in Ireland pig manure currently has no other use than as fertiliser.

National emissions for pigs and poultry, excluding application on soil as a fertiliser, are presented in Figure 1.4, based on data submitted to the European Environment Agency (2017). This shows a peak in pig emissions in the 1990s, which has been decreasing since then, with only a slight increase from 2015 to 2016. Poultry emissions, however, have been steadily increasing since 2008, reaching their maximum of 3.3 Gg in 2016.

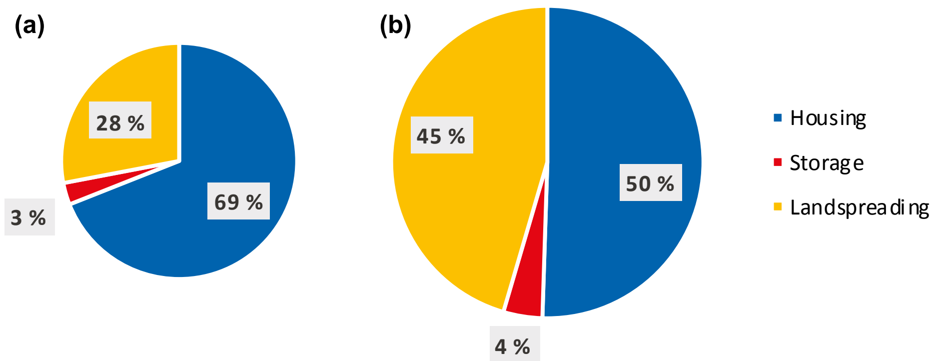

Figure 1.3. Estimated sources of ammonia emissions for (a) poultry and (b) pigs. Source: Hyde *et al.*, 2003.

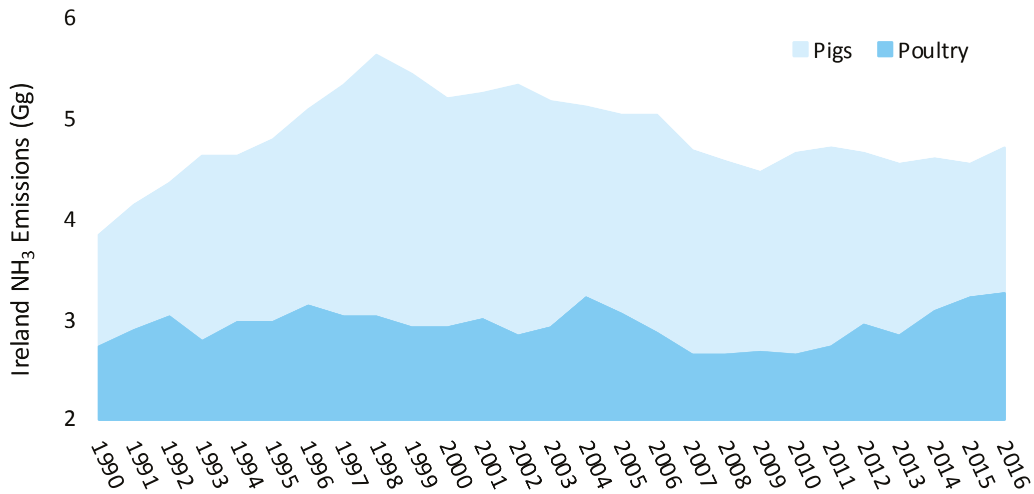

Figure 1.4. Irish ammonia emissions for pig and poultry production from 1990 to 2016 (European Environment Agency, 2017). These do not include emissions from manure applied to land.

1.3 Human Health Impacts

Air pollution has been linked to 1500 premature mortalities every year in Ireland while also contributing to illnesses resulting in reduced productivity and increased hospital visits (Department of Communications, Climate Action and Environment, 2017). It has been reported that particulate matter formed from ammonia is the most problematic element of agricultural emissions from a human health perspective (Stokstad, 2014). The very small particles that it contributes to (fine particulate matter – $PM_{2.5}$) have been shown to increase cardiovascular hospital admissions by 1% for every additional 10 µg NH_3 m^{-3} in the air (Dominici *et al.*, 2006). Additionally, a large-scale study (336,648 children) carried out in Denmark reported that exposure to high concentrations of both atmospheric ammonia and its particulate form, ammonium, increase the risk of asthma developing in young children (Holst *et al.*, 2018). This highlights that exposure to ammonia both as a gas and in particulate matter can have implications for public health. Ireland was listed ninth in the world for prevalence of asthma in children aged 13–14 years in 2000–2003 by the Global Strategy for Asthma Management and Prevention (GINA, 2016). The link between agricultural emissions and asthma has not yet been considered in Ireland and additional research is required to evaluate this potential link.

1.4 Environmental Impacts from Atmospheric Ammonia

Atmospheric ammonia can have an impact on the environment through both dry deposition of ammonia itself, alongside other nitrogenous compounds in addition to direct toxicity, and wet deposition of ammonium. A review paper published in 2010 states that “nitrogen accumulation is the main driver of changes to species composition across the whole range of different ecosystem types” (Bobbink *et al.*, 2010). These physical impacts include leaf necrosis, reduction in species richness, loss of species, encouraging nitrophytic plants and exacerbating other impacts (e.g. drought, frost, pathogens) (Krupa, 2003).

Direct toxicity to plants can occur with high concentrations of atmospheric ammonia, with necrosis of leaves observed on conifer trees. In the former German Democratic Republic, deforestation of areas as large as 200 ha was observed as a result of extensive pig farms housing 200,000 pigs (Krupa, 2003). Plant stress response to additional abiotic stresses has been shown to further affect heather (*Calluna vulgaris*) when concentrations of atmospheric ammonia exceed 8 µg NH_3 m^{-3} (Sheppard *et al.*, 2009). Sheppard *et al.*’s (2009) study also showed that dry deposition of atmospheric ammonia was of greater concern, as no effect was observed from enhancing nitrogen deposition in rainwater. Increased tissue concentration of nitrogen can increase plant susceptibility to frost, drought and pathogens (Krupa, 2003).

Threshold Indicator Taxa Analysis (TITAN) indicated both community changes and species loss below the currently used empirical critical loads (Wilkins *et al.*, 2016a). Although species richness of 68 acid grasslands across the UK displayed a linear relationship between nitrogen increase and species loss, one species lost per quadrat for every 2.5 kg N ha^{-1} $year^{-1}$ was observed (Stevens *et al.*, 2004). Species composition is also greatly affected by increasing atmospheric ammonia concentrations, with oligotrophic species being replaced by nitrophytic species. A UK study observed that flora was dominated by nitrophytic species when concentrations exceed 3 µg NH_3 m^{-3} on woodland ground flora (Pitcairn *et al.*, 2009). Given time and consistently high concentrations, this can cause habitat changes; for example, both wet and dry heathlands in the Netherlands have transitioned to grasslands (Krupa, 2003). Similarly, grass encroachment has been observed in stable dune grasslands, where, although an increase in biomass in some species was observed, there was a loss in biomass in other species combined, with biomass production decreasing over 3 years when exposed to 20–40 kg N ha^{-1} $year^{-1}$ (van den Berg *et al.*, 2005).

In a UK study by Jones *et al.* (2013) – which showed that dune grassland species utilised ammonia as a nutrient source – the ammonia emissions from an intensive poultry unit (12 houses, 160,000–180,000 bird capacity) were detected up to 2.8 km upwind, contributing to exceedance of the lower critical level of 1 µg m^{-3} of ammonia within 800 m and an exceedance of critical loads of nitrogen 2.8 km upwind. This highlights that impacts are not restricted to areas downwind of such intensive hotspots. Studies have shown impacts from atmospheric ammonia on a number of different habitat types, including woodlands, grasslands, bogs and uplands (Sutton *et al*., 2011; Henry and Aherne, 2014; Wilkins *et al*., 2016b; Stiles *et al*., 2017). Downwind of a poultry farm in Northern Ireland, epiphytic lichens on trees were replaced with a green algal slime, in addition to algal growth over decaying peat moss (*Sphagnum*) leading to its eventual decay and loss from site and also bleaching of reindeer lichen (*Cladonia* spp.) (Sutton, 2007; Sutton *et al*., 2011).

Nitrogen deposition as a whole causes declines in species diversity, increased susceptibility to secondary stresses and altered soil processes (Jones *et al*., 2013). Both national and international research has linked nitrogen pollution to species declines (Bobbink *et al*., 2010; Maskell *et al*., 2010; Henry and Aherne, 2014; Hernández *et al*., 2016; Aherne *et al*., 2017). When ammonia and ammonium particulates are deposited onto the soil, ammonium nitrification may occur. This oxidation process can result in soil acidification and possible long-term plant nutrient imbalances of calcium, potassium and magnesium (van der Molen *et al*., 1990). The acidification and eutrophication of ecosystems caused by the deposition of atmospheric nitrogen is of significant consequence to ombrotrophic systems, such as heaths and bogs, because these systems are particularly susceptible to elevated nitrogen inputs (van den Berg *et al*., 2005).

1.5 Ecological Indicators

The impact of atmospheric nitrogen and ammonia on vegetation has resulted in a suite of potential ecological indicators capable of identifying eutrophication or acidification as a result of increased concentrations and deposition. The sensitivity of lower plants such as bryophytes and lichens to atmospheric pollution has been utilised in a number of studies and guides as indicators of nitrogen pollution through species or community changes; this is in addition to biochemical impacts on the plants (Søchting, 1995; Britton and Fisher, 2010; Edmondson *et al*., 2010).

The UK Centre for Ecology & Hydrology has developed a field guide to identify impacts from atmospheric nitrogen, based on lichens present (UK Centre for Ecology & Hydrology, 2015). In some cases impacts on a species level are obvious and the application of parameters such as species richness can be indicative of impacts. For example, bryophyte species richness has been shown to be negatively correlated with nitrogen deposition on Welsh heathlands, along a gradient of 19.5 to 30.5 kg N ha^{-1} $year^{-1}$ (Edmondson *et al*., 2010).

A 2010 Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) report described epiphyte biomonitoring with the aim of identifying the effects of nitrogen on terrestrial habitats. The study showed a stronger association of lichens with atmospheric ammonia on birch trees than on oak trees, which was mirrored by their association with bark pH (Lewis *et al*., 2010). Studies have also analysed nitrogen concentrations in plants as a response to atmospheric conditions, and found that for example, both atmospheric concentration and deposition of nitrogen influenced nitrogen concentration in the thallus of lichens studied (Britton and Fisher, 2010). A study in the Scottish heathlands identified a response from terricolous (growing on the ground) lichens responding to a critical load of 7.5 kg N ha^{-1} $year^{-1}$ and the study suggests their use as an indicator of deposition and impact on Alpine heathlands on account of species-specific responses and tolerance (Britton and Fisher, 2010). Reindeer lichen (*Cladonia portentosa*) and tube lichen (*Hypogymnia physodes*) have been used as indicators of nitrogen impacts in Denmark, where the nitrogen content of the plants was analysed; it was concluded that the elevated concentrations inside the plants may have been due to dry deposition of ammonia (Søchting, 1995).

Nitrogen content in bryophytes has been used to identify impacts from intensive livestock farms in the UK. A study showed a decrease in foliar nitrogen content from 4% to 1% within 1 km, where concentrations decreased from 24–59 µg NH_3 m^{-3} to 1.6–5 µg NH_3 m^{-3} over the same distance (Pitcairn *et al*., 2006a). Transplanted tube lichens (*H. physodes*) in Denmark were capable of identifying a gradient of nitrogen pollution downwind of a pig farm, probably from the farm's contribution to dry deposition of ammonia (Søchting, 1995). In Ireland, lichens were collected from twigs in the EpiAir study, as part of the broader Tellus project that examined chemical and physical properties of Ireland's soil, rocks and water. The Tellus border project was carried out in five counties along Ireland's border with Northern Ireland. The EpiAir project analysed 700 twig samples collected; 932 nitrophytic species were identified, compared with only 56 oligotrophic species (Fox and

Cullen, 2013). A Nitroindex value developed by a Swiss study (Rihm *et al.*, 2009) was applied, where a value of –1 is representative of a community not affected by nitrogen and +1 indicates an impact. To calculate the Nitroindex, the frequency of oligotrophic values is subtracted from nitrophytic species and divided by the sum of all frequencies; in this case the Nitroindex was 0.9, a clear indicator of impacts from nitrogen in Ireland's border counties.

1.6 Critical Levels

A critical level is defined as "the concentration in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems or materials, may occur according to present knowledge" (Posthumus, 1988). Critical levels have historically been set to cover multiple time periods, including hourly (3300 μg $NH_3\,m^{-3}$), daily (270 μg $NH_3\,m^{-3}$), monthly (23 μg $NH_3\,m^{-3}$) and annually (Posthumus, 1988).The use of annual critical levels has been recommended primarily because of the significance of long-term over short-term impacts (Hayes *et al.*, 2017). The United Nations Economic Commission for Europe (UNECE) currently recommends the use of annual critical levels of 1 and 3 μg $NH_3\,m^{-3}$, depending on species sensitivity (United Nations Economic Commission for Europe, 2007). This is a decrease from the annual critical level of 8 μg $NH_3\,m^{-3}$, based on findings from a 2006 UNECE Expert Workshop in Edinburgh. This workshop will be referred to as the "Edinburgh workshop" (Sutton *et al.*, 2009a). This workshop clarified that the higher critical level of 3 μg $NH_3\,m^{-3}$ is an average of observed impacts between 2 and 4 μg $NH_3\,m^{-3}$; the lower end of this scale was set based on impacts occurring on heather (*C. vulgaris*) when exposed to this concentration.

The Edinburgh workshop allowed contributing members to prepare background documents and targeted papers, where these acted as a base for the workshop summary, to be published as the book *Atmospheric Ammonia: Detecting Emissions Changes and Environmental Impacts* (Sutton *et al.*, 2009a). This book presents studies that support the reduction of critical levels from 8 μg $NH_3\,m^{-3}$. Evidence for this reduction is based primarily on observed changes to species composition in the field, where changes were observed at much lower concentrations than 8 μg $NH_3\,m^{-3}$. A critical level of 1 μg $NH_3\,m^{-3}$ is intended to protect habitats where lichens or bryophytes form a key part of the ecosystem (Cape *et al.*, 2009). For example, this critical level can be applied to habitats such as bogs, where *Sphagnum* mosses act as "ecosystem engineers" (Jones *et al.*, 1994), or Atlantic oak woodlands, where lichens form extensive epiphytic communities (Mitchell *et al.*, 2005). This was supported for Mediterranean lichen communities where a critical level of 1.4 μg $NH_3\,m^{-3}$ was observed to affect lichen diversity (Pinho *et al.*, 2009). A national and farm-scale study of lichen diversity on tree trunks and twigs was also used to support the use of a critical level of 1 μg $NH_3\,m^{-3}$, where impacts were observed at 1.15 μg $NH_3\,m^{-3}$ for lichens on trunks and impacts on lichens on twigs were estimated to occur at 0.7–1 μg $NH_3\,m^{-3}$ for lichens on twigs (Sutton *et al.*, 2009b). Further support was provided by a study on a bog in Whim, Scotland, where a critical level of 0.8 μg $NH_3\,m^{-3}$ was identified (Leith *et al.*, 2004). The impact of ammonia on lichen species is two-fold, through both altering bark pH and eutrophication (Sutton *et al.*, 2009b).

Recent research on epiphytic lichen communities within Mediterranean evergreen woodlands originally identified a critical level lower than 1.9 μg $NH_3\,m^{-3}$ (Pinho *et al.*, 2012), which was later reduced to 0.69 μg $NH_3\,m^{-3}$ based on further research and extending the scale of assessments (Pinho *et al.*, 2014). A Spanish study showed a critical level of 2.6–3.1 μg $NH_3\,m^{-3}$ for lichen species within a holm oak forest, which is higher than the range of 0.69–1.9 μg $NH_3\,m^{-3}$ previously identified (Aguillaume *et al.*, 2017); this may represent a critical level for an already affected area. This is probably the result of the pre-existing loss of nitrogen-sensitive species, which is likely in an area with historic nitrogen pollution.

A critical level for higher plants was more difficult to select because of the availability of less evidence at the time of direct impacts and thus was based primarily on expert judgement; it was set at 3 μg $NH_3\,m^{-3}$, presuming uncertainty within the range of 2–4 μg $NH_3\,m^{-3}$. This decision was primarily based on an English study in which impacts on woodland ground flora were not observed at concentrations greater than 4 μg $NH_3\,m^{-3}$ (Pitcairn *et al.*, 2006b) and the no-effect concentration for *C. vulgaris* 2 μg $NH_3\,m^{-3}$ (Sheppard *et al.*, 2009). Monitoring of ambient concentrations of atmospheric ammonia was conducted on 26 sites in Ireland during the period 2013–2014; only three sites were below the critical level of 1 μg NH_3 m^{-3}. Although no site experienced concentrations above 3 μg NH_3 m^{-3}, nine sites exceeded 2 μg NH_3 m^{-3} (Doyle *et al.*, 2017). A 1999 study indicated a broader range of concentrations, ranging from 0.18 to 3.212 μg NH_3 m^{-3} (de Kluizenaar and Farrell, 2000). In both studies critical levels were exceeded without the contribution from pig and poultry farming, as monitoring was intentionally conducted at least 2 km from any such point sources. The concentrations observed were hence primarily from land spreading of slurry and cattle farming. Other projects that monitored concentrations in Northern Ireland recorded concentrations of 4.8 and 6.7 μg NH_3 m^{-3} upwind of point sources (Tang *et al.*, 2005).

1.7 Critical Loads

A critical load is defined as "a quantitative estimate of deposition of one or more pollutants below which significant harmful effects on specified elements of the environment do not occur according to present knowledge" (Posthumus, 1988). Critical loads refer to total nitrogen deposited from the air, whereas critical levels refer only to atmospheric concentrations of ammonia. Critical loads are more complex than the use of critical levels, as they require calculations to be carried out using the concentrations present. In contrast, critical levels can be directly applied to the concentrations of ammonia monitored or modelled in an area. Deposition of atmospheric ammonia occurs by two mechanisms – wet deposition and dry deposition. Wet deposition refers to the loss of nitrogen from the air through rainfall typically as ammonium, which is of primary concern in areas with few sources of ammonia. Dry deposition pertains to atmospheric nitrogen being deposited directly onto the ground or plant surfaces, primarily by diffusion, and has a greater impact on areas with high sources of ammonia (Krupa, 2003). Reduced nitrogen deposition is representative of summing both wet deposition of ammonium and dry deposition of ammonia, where total nitrogen deposition is calculated by summing both reduced and oxidised nitrogen. Total nitrogen deposition is then used to assess critical load exceedance.

In Ireland, wet deposition of ammonium has been calculated by interpolating ammonium concentrations across the country and combining long-term annual rainfall data from Met Éireann, whereas dry deposition of ammonia is mapped by interpolating monitored ammonia concentrations and applying surface-specific deposition velocities (Doyle *et al.*, 2017). Total reduced nitrogen across Ireland ranges from 2 to > 12 kg N ha^{-1} $year^{-1}$, with dry deposition estimated to account for 60% of reduced nitrogen deposition in Ireland (Doyle *et al.*, 2017). Empirical critical loads have been identified for European Nature Information System (EUNIS) habitat types ranging from 3 to 30 kg N ha^{-1} $year^{-1}$ (Bobbink and Hettelingh, 2011). These critical loads can be directly applied to the habitats listed for protection in Annex I of the EU Habitats Directive (EU, 1992). Species change points have been identified for eight Annex I habitats below the relevant empirical critical loads in Ireland (Wilkins *et al.*, 2016a). For 12 of the habitats tested, a range of 5–30 kg N ha^{-1} $year^{-1}$ is recommended by Bobbink and Hettelingh (2011), whereas TITAN indicates species change points in a range of 3.9–15.3 kg N ha^{-1} $year^{-1}$ (Table 1.1). This indicates that the use of critical loads may need to be refined to ensure that there is no further loss of biodiversity across Europe.

Ireland, as an EU Member State, complies with the European Monitoring and Evaluation Programme (EMEP) under the CLRTAP. Five EMEP monitoring stations currently operate in Ireland; these are used to calculate the exceedance of critical loads on a 50 × 50 km grid (Aherne *et al.*, 2017).

1.8 Natura 2000 Sites in Ireland

Natura 2000 sites are composed of Special Protection Areas (SPAs) designated under the EU Birds Directive (2009/147/EC; EU, 2009) and Special Areas of Conservation (SACs) designated under the EU Habitats Directive (EU, 1992). Both directives have been transposed into Irish law by the European Communities (Birds and Natural Habitats) Regulations 2011 (Government of Ireland, 2011). Ireland currently has 430 sites designated as SACs and 153 as SPAs, covering *c.*14% of the country. The Habitats Directive requires these sites to achieve and maintain a favourable conservation status, which is based on the success of each site's qualifying features. Natura 2000 sites are subject to more stringent environmental protection than any other site in Ireland.

Under Article 6(3) and 6(4) of the Habitats Directive, any plan or project not directly connected to or necessary for the management of a Natura 2000 site "likely to have a significant effect" (EU, 1992) thereon

Table 1.1. Species change points and critical loads for Annex I habitats

Annex I code	Annex I habitat	Critical load (kg N ha^{-1} $year^{-1}$)	Species change point (kg N ha^{-1} $year^{-1}$)
4010	Northern Atlantic wet heaths with *Erica tetralix*	10–15	4.9
4030	European dry heaths	10–20	4.1
4060	Alpine and boreal heaths	5–15	5.5
5130	*Juniperus communis* formations on heaths or calcareous grasslands	10–20	4.8
6210	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*)	15–25	8.3
6230	Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas (and submountain areas in continental Europe)	10–15	3.9
6410	*Molinia* meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caeruleae*)	15–25	6.3
6510	Lowland hay meadows (*Alopecurus pratensis*, *Sanguisorba officinalis*)	20–30	7.5
7130	Active blanket bogs	5–10	4.9
8210	Calcareous rocky slopes with chasmophytic vegetation	5–10	5.7
91A0	Old sessile oak woods with *Ilex* and *Blechnum* in the British Isles	10–15	8.8
91E0	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, *Alnion incanae*, *Salicion albae*)	NA	15.3

Critical load refers to empirical critical load range recommended by Bobbink and Hettelingh (2011) and species change point refers to the deposition rate above which impacts on species composition occurred.

NA, not applicable.

Adapted from Wilkins *et al.* (2016a).

requires a process known as “appropriate assessment” (AA). As part of the AA process – required for both planning and licence applications – stage 1 screening must be carried out in order to conduct a preliminary assessment of impacts on Natura 2000 sites. If impacts on the qualifying features of the site cannot be ruled out at this point, the plan or project can be denied or a full AA is required. Consent for a plan or project can only be given after having determined that the plan or project would not adversely affect the integrity of a Natura 2000 site. This level of impact assessment is required only for Natura 2000 sites and is not legally required for other sensitive sites, such as Natural Heritage Areas (NHAs) or proposed Natural Heritage Areas (pNHAs).

Ireland has 59 habitats and 51 species listed in Annexes I and II of the Habitats Directive; these are both SACs and SPAs. The most recent assessment under the Habitats Directive showed that 85% of habitats and 30% of species have an unfavourable conservation status (Department of Culture Heritage and the Gaeltacht, 2019). Breeding bird populations that are protected by SPAs show a 27% decrease, with 24% of wintering birds decreasing (Department of Culture Heritage and the Gaeltacht, 2017).

Although impacts of atmospheric nitrogen deposition on SPAs are primarily considered to be secondary by reducing suitable habitats available they can influence the conservation objectives for that site. For example, replacing heathland with grassland (Heil and Diemont, 1983) could potentially influence breeding bird populations (Olff and Ritchie, 2002). Direct impacts on habitats and species, in particular those with lichen and moss communities, are a more obvious threat (Sutton *et al*., 2011; Sheppard *et al*., 2009; Hernández *et al*., 2016). As 85% of habitats within the Natura 2000 network are currently viewed as having unfavourable conservation status, the cumulative impact of atmospheric ammonia is probably exacerbating other impacts on the sites (Krupa, 2003). AA requires the consideration of cumulative impacts, whereby all sources of atmospheric ammonia would need to be considered in addition to the emissions from the development seeking approval. Other EU Member States have adopted policies of monitoring (Lolkema *et al*., 2015) or modelling (Hallsworth *et al*., 2010; García-Gómez *et al*., 2014) impacts on the Natura 2000 network of sites based on atmospheric ammonia and nitrogen deposition. Ireland has not yet produced an assessment of the ammonia or nitrogen impact on Natura 2000 sites.

1.9 National Monitoring and Modelling

Ireland conducts monitoring at five locations under EMEP as part of the CLRTAP. Excluding Oak Park in County Carlow, all EMEP sites are currently on Ireland's coastline. These sites monitor a range of pollutants both in the air and precipitated through rainfall. Valentia, Oak Park, Glenveagh and Wexford monitor wet deposition of NO_3^- and NH_4^+, whereas concentrations of these in the air are recorded in Oak Park, Mace Head, Carnsore Point (Wexford) and Malin Head (Glenveagh). These sites do not currently measure atmospheric ammonia, but NO_x and NO are both monitored at Mace Head (O'Leary, 2010).

Atmospheric monitoring of ammonia has been conducted twice in Ireland, once in 1999–2000 (de Kluizenaar and Farrell, 2000) and a second time in 2013–2014 (Doyle *et al*., 2017). Both studies used Willems' badges (Willems, 1989, 1993), a passive ammonia sampling technique. The Willems' badge uses a filter paper soaked in tartaric acid, which reacts with ambient air through a polytetrafluoroethylene (PTFE) membrane absorbing ambient ammonia. Spectrophotometric analysis of samples was used to determine the ammonia concentration at 40 sites in 1999–2000 and 26 in 2013–2014. Of the original 40 sites monitored, 15 fell below the critical level of $1\,\mu g\,NH_3\,m^{-3}$ and only four sites exceeded the critical level of $3\,\mu g\,NH_3\,m^{-3}$. When repeated in 2013–2014, on fewer sites, no exceedance of $3\,\mu g\,NH_3\,m^{-3}$ was observed and only three sites fell below $1\,\mu g\,NH_3\,m^{-3}$. This is probably because of the overall number of sites monitored, as no significant difference was observed on sites where monitoring was repeated (Doyle *et al*., 2017). Both these projects investigated ambient concentrations of atmospheric ammonia on sites that were at least 2 km from an intensive point source, such as a pig or poultry farm (de Kluizenaar and Farrell, 2000). Meanwhile, continuous monitoring of ammonia on 85 sites has occurred across the UK since 1996. The UK network uses a combination of ALPHA (Adapted Low-cost Passive High Absorption) and DELTA (Denuder for Long-term Atmospheric – sampling) samplers. ALPHA samplers, similar to Willems' badges, are passive diffusion ammonia samplers where citric acid forms the reactive surface for ammonia. A DELTA sampler is a low-volume denuder where a known volume of air is passed through the sampler and reacts with a coating within the denuder. The UK cross-calibrated concentrations recorded by ALPHA samplers were compared with those recorded by DELTA samplers on 12 sites within its monitoring network.

Because of the large spatial variability of atmospheric ammonia on account of agriculture, it is not possible to infer concentrations from a monitoring network alone. Therefore, the UK has developed the FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) model, which is calibrated against the UK monitoring network (Singles *et al*., 1998). A similar approach has been used in Switzerland, where the modelled ammonia concentrations did not vary significantly from 40 sites where passive samplers were used to monitor local concentrations (Thöni *et al*., 2004). FRAME, supported by the national monitoring network, has allowed the UK to accurately gauge the risk to Natura 2000 sites from atmospheric ammonia (Hallsworth *et al*., 2010), with 59.1% of sites exceeding a critical level of $1\,\mu g\,NH_3\,m^{-3}$ and 9.8% exceeding $3\,\mu g\,NH_3\,m^{-3}$. FRAME has been used to model concentrations of atmospheric ammonia in Ireland for 1996 (Fournier *et al*., 2002), indicating concentrations of $0–8\,\mu g\,NH_3\,m^{-3}$. At the time that modelling was conducted, emissions from pig and poultry farms were subject to artificial smoothing, as the locations of pig and poultry houses were not available.

The FRAME model used by the UK is a Lagrangian atmospheric transport model capable of assessing long-term annual mean deposition of nitrogen over the UK. It has also been adapted to model transport and deposition of heavy metals, particles, sulfur, greenhouse gases, etc. FRAME has proven itself to be a useful atmospheric transport model and is applied to other countries, including Poland (Kryza *et al*., 2011) and China (Zhang *et al*., 2011). Other countries have developed their own national models to gauge concentrations and deposition of ammonia and other forms of nitrogen. Denmark utilises a local-scale Gaussian dispersion–deposition model coupled with a regional chemistry transport model, known collectively as DAMOS (Danish Ammonia Modelling System). This system estimates the ammonia concentration and deposition across Denmark with a spatial resolution of 400 m × 400 m. Similar to the UK method of combining monitoring with modelling, DAMOS has been validated by Denmark's network of ammonia sampling sites monitored using ALPHA samplers (Geels *et al*., 2012). The OPS (Operational Priority Substances) model is used in the Netherlands and is also validated by continuous monitoring at eight locations (Wichink Kruit *et al*., 2017). The Dutch National Air Quality Monitoring Network has been using a wet annual denuder system on the eight monitoring locations since 1992 to support national modelling (Buijsman *et al*., 1998), with ambient concentrations varying between 2 and 4 µg NH_3 m^{-3}, increasing to between 10 and 25 µg NH_3 m^{-3} in agricultural areas.

Eulerian models on a European scale, such as the LOTOS-EUROS model, are intended to identify long-range transport and deposition of ammonia, whereas Lagrangian models, such as FRAME, are best suited to describing concentrations and deposition with a higher spatial resolution (Sutton *et al*., 2009a). The LOTOS-EUROS model has been improved by incorporating the bi-directional surface–atmosphere exchange, but it still underpredicts concentrations in agricultural areas and overpredicts in unaffected areas (Wichink Kruit *et al*., 2012).

1.10 Local Monitoring and Modelling

In addition to national monitoring and modelling programmes, a number of smaller projects measuring or modelling concentrations of atmospheric ammonia are often conducted. Monitoring of local concentrations has generally taken two approaches: concentrations are measured firstly downwind of intensive point sources (Tang *et al*., 2005) and secondly on sensitive Natura 2000 sites (Lolkema *et al*., 2015). Some studies can, however, be classified as a combination of both (Jones *et al*., 2013).

There are multiple models available to simulate the dispersion of pollutants, including ammonia, from intensive point sources. Two models commonly used are ADMS (Atmospheric Dispersion Modelling System) (Carruthers *et al*., 1994) and AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model) (Cimorelli *et al*., 2002). Both these models are advanced Gaussian dispersion models. Despite differences in predictions, both these models have been deemed “acceptable” when simulating short-range atmospheric dispersion of ammonia from agricultural sources when compared with monitored concentrations (Theobald *et al*., 2012). However, predictions from AERMOD are generally higher than those from ADMS and when both models were used to compare the dispersion from a pig farm, AERMOD more accurately predicted concentrations (Theobald *et al*., 2015).

Monitoring was conducted on two farms in Northern Ireland, comparing natural and mechanical ventilation systems and their influence on nearby concentrations of atmospheric ammonia (Tang *et al*., 2005). This study using ALPHA samplers showed that concentrations at 300 m downwind of both farms were lower near the mechanically ventilated farm, at 4.8 µg NH_3 m^{-3}, than at the naturally ventilated building, with concentrations of 7.1–9.8 µg NH_3 m^{-3}. The ambient concentrations of ammonia were high for both these farms, with ambient concentrations of 4.8 µg NH_3 m^{-3} from the mechanically ventilated farm and 6.7 µg NH_3 m^{-3} from the naturally ventilated farm 320 m downwind. This study highlighted that, although discrepancies existed when comparing monitored with modelled concentrations generated using ADMS, modelling was a “reasonable and useful predictive tool”. This work was later used to validate the Simple Calculation of Atmospheric Impact Limits (SCAIL)-Agriculture dispersion model (Hill *et al*., 2014).

Since 2005, monitoring has been conducted on Natura 2000 sites in the Netherlands (Lolkema *et al*., 2015). In 2014, the Measuring Ammonia in Nature (MAN) project had expanded to include 236 sampling points across 60 Natura 2000 sites. This study used Gradko passive samplers, required in triplicate on each site since 2011. Because of the uncertainty in a single MAN measurement using Gradko samplers, calibration was conducted with ALPHA samplers in four locations over the course of more than 2 years. This study described the use of ALPHA samplers as being slightly more difficult than the use of Gradko samplers; however, as videos instructing on their use have now been added to the UK Centre for Ecology & Hydrology website, this should reduce this problem in future (UK Centre for Ecology & Hydrology, 2018). A Natura 2000 site in Wales located within 600 m of an intensive poultry farm housing between 160,000 and 180,000 birds was monitored using both ALPHA and Gradko passive samplers for 12 months (Jones *et al*., 2013). Sampling conducted at 300 m, 800 m and 2800 m upwind of the farm indicated decreasing concentrations of 6.3 µg NH_3 m^{-3}, 1.2 µg NH_3 m^{-3} and 0.9 µg NH_3 m^{-3}, respectively. The boundary of the Natura 2000 site occurs at the 800 m sampling point, where the critical level of 1 µg NH_3 m^{-3} was exceeded by 0.2 µg NH_3 m^{-3}; at this sampling point, the study estimates a contribution of 0.6 µg NH_3 m^{-3} from the poultry house.

Moninea Bog SAC, located to the immediate east of an intensive poultry farm in Northern Ireland, provided a case study for monitoring impacts on a lowland raised bog. Assessment of impacts on this site took the form of visual assessments, analysing plant nitrogen accumulation, monitoring atmospheric ammonia and modelling the dispersion from the poultry house (Sutton *et al*., 2011). Visual impacts were evident directly beside the poultry house, where a thick algal slime had accumulated on nearby birch trees. It was estimated that, within 200 m of the farm, 90% of *Cladonia* and *Sphagnum* spp. were affected. Nitrogen content within plants reached 4% near the house, which on an unaffected site was between 0.5% and 1%. Monitored concentrations of atmospheric ammonia conducted using ALPHA samplers were consistent with modelling completed using ADMS, where concentrations closest to the farm ranged between 14 and 34 µg NH_3 m^{-3}, reducing to between 1 and 4 µg NH_3 m^{-3} at *c*.670 m from the farm.

1.11 SCAIL-Agriculture

SCAIL-Agriculture (see Figure 1.5) is a tool developed by the UK Centre for Ecology & Hydrology for use in both the UK and Ireland (it is currently being adapted for use in Sweden) (Hill *et al*., 2014). It utilises AERMOD to model ammonia emissions from livestock housing (pig, poultry and cattle). It is intended as a screening tool that is particularly useful for the stage 1 screening required by the Habitats Directive on Natura 2000 sites. It is also useful for environmental assessments required under IED licence applications and environmental impact statements, as an indication of the requirement for detailed dispersion modelling.

SCAIL-Agriculture utilises 40 meteorological stations across the UK and Ireland to predict wind direction and strength. It does not consider the depletion of ammonia through deposition or its conversion to ammonium, in addition to discounting impacts from wet deposition of ammonia (Hill *et al*., 2014). SCAIL-Agriculture uses the FRAME concentration model to estimate ambient concentrations for the UK, whereas the only recent data available for Ireland are interpolating concentrations between monitoring points of the 1999–2000 (de Kluizenaar and Farrell, 2000) and 2013–2014 (Doyle *et al*., 2017) monitoring studies. In order for assessments to be compliant with the Habitats Directive, they need to give cognisance to cumulative impacts, which was never the intention of the SCAIL-Agriculture tool.

1.12 Emissions Monitoring

In order to utilise an atmospheric dispersion model such as AERMOD, ADMS and SCAIL-Agriculture, it is important to know both the emission rate and the ventilation rate of intensive agriculture units. The ammonia emission rate is the product of overall ventilation rate and ammonia concentration (Krause and Janssen, 1989), allowing for methods other than direct emission monitoring. In order to calculate the emission rate, both the ventilation rate of the house and the indoor ammonia concentration need to be monitored simultaneously. SCAIL-Agriculture provides emission and ventilation rates based on UK and Irish studies (Hill *et al*., 2014), where emission factors are presented as average annual emission rates. A number of methods have been used to monitor the ventilation rates from intensive pig and poultry farms, for example direct monitoring of exhausts using fan wheel anemometers (Demmers *et al*., 1999; Mol and Ogink, 2004) and the use of mass balance approaches (Groot Koerkamp *et al*., 1998b; Seedorf *et al*., 1998; Gates *et al*., 2005). In some studies, outdoor concentrations of ammonia have been used to correct the emission rate (Groot Koerkamp *et al*., 1998b), whereas others have presumed zero contribution from ambient concentrations (Hayes *et al*., 2006a,b).

An extensive survey of 329 livestock buildings across Europe was conducted between 1992 and 1996; this showed an agreement to within 6% of fan wheel anemometers and CO_2 mass balance (Wathes *et al*., 1998). The use of other tracer gases has been shown to underestimate ammonia emissions when compared with fan wheel anemometers (Demmers *et al*., 1999). Heat, moisture and CO_2 mass balance techniques can be used to calculate the ventilation rate on a 24-hour basis for insulated buildings. However, for buildings that are uninsulated, it recommends the use of only CO_2 mass balance on account of difficulties in estimating heat loss from the building (Pedersen *et al*., 1998). The use of CO_2 mass balance is often the most suitable method for monitoring ventilation rates, as, although fan wheel anemometers can be better indicators of ventilation rates, they have a number of limitations. For example, the number of anemometers

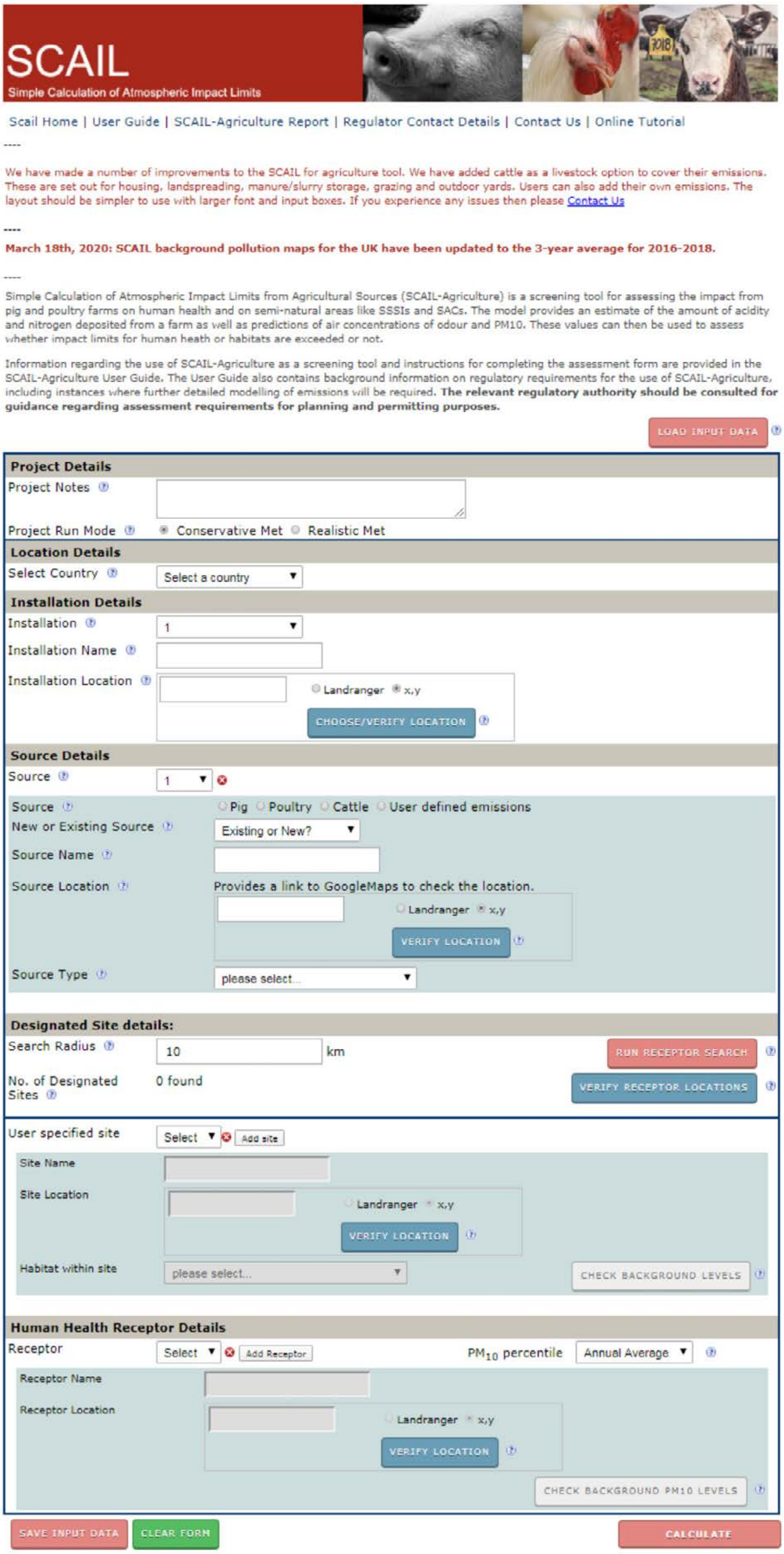

Figure 1.5. Layout of SCAIL-Agriculture online tool.

may be significant depending on the number of outlets in the building and they are not suitable for naturally ventilated buildings (Phillips *et al*., 1998). The use of a CO_2 mass balance has been described as "the only suitable technique for surveys because it is straightforward and low cost" (Seedorf, 1998); this study points out that fan wheel anemometers may be useful when monitoring single houses for long periods of time, rather than short-term monitoring as part of a study. SCAIL-Agriculture uses the ventilation rates monitored by Seedorf *et al*. (1998) on 329 livestock buildings across Northern Europe (Hill *et al*., 2014).

A review of methods for measuring emission rates from livestock buildings identifies that measuring the ratio of a tracer gas emitted from a building is the best method for determining emissions, while the second-best method involves determining the flux of ammonia by monitoring both the ventilation rate and ammonia concentrations (Phillips *et al*., 2000). Monitoring indoor concentrations of atmospheric ammonia can be done with numerous devices, all with their own inherent benefits and flaws. Electrochemical sensors have been used in the USA and these need to be cyclically purged with clean air (Gates *et al*., 2005). The only Irish study that monitored ammonia concentrations within operational intensive farm units used a chemiluminescent ammonia analyser (iTX) (Hayes *et al*., 2006a,b) for 24-hour periods. A number of studies utilise photo-acoustic analysis, which allows for long-term monitoring of ammonia concentrations (van der Peet-Schwering *et al*., 1999; Li *et al*., 2015; Pereira *et al*., 2017). Off-axis Integrated Cavity Output Spectroscopy (OA-ICOS) has also been used to monitor atmospheric ammonia concentrations (Baer, 2012); this was recently used by Ricardo-AEA in the UK on behalf of the Department for Environment, Food & Rural Affairs in order to monitor emissions from poultry buildings (A. Leonard, Ricardo, 21 October 2014, personal communication). OA-ICOS, in the form of a Los Gatos Research (LGR) ultraportable ammonia analyser, outperformed a number of other ammonia sensors in field trials in Edinburgh under the supervision of the UK Centre for Ecology & Hydrology (Twigg *et al*., 2018), during which it showed the lowest relative deviation from the mean compared with a number of other advanced sensors.

The emission factors currently recommended for use by the EPA for above-threshold farmers submitting data as part of annual environmental reporting are the result of an expert panel in 2009 (B. Hyde, EPA, 26 February 2014, personal communication), primarily informed by those used in the UK at the time (Misselbrook *et al*., 2004) but also those that incorporated available Irish emission rates (Hayes *et al*., 2004; O'Connell *et al*., 2007; Garry *et al*., 2007; Leek *et al*., 2007; Lynch *et al*., 2007a,b,c; O'Shea *et al*., 2009). Ammonia emissions from Irish pig and poultry houses were last monitored in 2006 (Hayes *et al*., 2006a,b); these studies used measurements taken on a number of days throughout the production cycle for pigs and poultry. At the time these results were not included in the EPA emission factor calculations, but they have since been incorporated into SCAIL-Agriculture. The AmmoniaN2K project aims to test the suitability of the emission factors currently recommended by the EPA, comparing them with those used by the SCAIL-Agriculture project, with a focus on comparing them with monitoring specifically carried out in Ireland (Hayes *et al*., 2006a,b).

1.13 Emission Reductions

With the exceedance of the ammonia emissions limit since 2016, it is vitally important that Ireland gives serious consideration to a number of possible ammonia abatement strategies. There are a number of strategies, listed in Tables 1.2 and 1.3 (in addition to those outlined in best available technique – BAT – guidance), which range in effectiveness from *c*.10% to 100% reduction in ammonia emissions. These are primarily focused on emissions from both housing and land spreading from pig and poultry farms, but manure spreading approaches for cattle are also integrated. Emissions from land spreading cattle manure can be reduced by 28–40% when using trailing shoe spreading instead of splashplate spreading (Dowling *et al*., 2008). Immediate ploughing of dry manure can further reduce emissions by *c*.13% (Cowell and Apsimon, 1998). Approaches to reducing emissions from housing cover the following three stages of the livestock production process: (1) reduce nitrogen entering the system; (2) reduce emissions during production by use of additives or drying; and (3) remove ammonia from the air as it leaves the building. Dietary manipulation is a popular approach to reduce emissions, where the amount of nitrogen entering the production system can be controlled by, for example, moderation of the crude protein content in food, which can reduce emissions by 35% (Table 1.2)

Table 1.2. Approaches to reducing ammonia emissions from poultry production, with reported percentage reduction in emissions

Approach	Reduction (%)	Source
Immediate ploughing of solid waste	13	Cowell and Apsimon (1998)
Increasing dietary fibre	14.3	Li *et al*. (2012)
Conversion to stilt housing	15	Cowell and Apsimon (1998)
Air scrubber	15–45	Ullman *et al*. (2004)
Nipple-drinking systems	16	Cowell and Apsimon (1998)
Reducing crude protein from 22% to 18%	35	Elwinger and Svensson (1996)
Replacing bell drinkers with nipple-drinking systems	35	Elwinger and Svensson (1996)
Incorporating acidifier into diet	39.2	Li *et al*. (2012)
Cleaning air using oxidants	58	Ullman *et al*. (2004)
Enhancing internal air circulation – broilers	70	Groot Koerkamp and Groenestein (2008)
Multi-stage scrubbers	70–100	Zhao *et al*. (2011)
Manure drying (caged laying hens, daily manure removal)	73–86	Groot Koerkamp *et al*. (1998a)
Adding aluminium sulfate to litter before crop	72	Madrid *et al*. (2012)
Adding aluminium sulfate to litter before crop	99	Ullman *et al*. (2004)
Covering manure	99	Ullman *et al*. (2004)

Table 1.3. Approaches to reducing ammonia emissions from pig production, with reported percentage reduction in emissions

Approach	Reduction (%)	Source
Low-emission spreading	10	Cowell and Apsimon (1998)
Reducing crude protein in diet	11–17	van der Peet-Schwering *et al*. (1999)
Immediate ploughing of solid waste	13	Cowell and Apsimon (1998)
Low-tech covering for slurry tanks	16	Cowell and Apsimon (1998)
Slurry aeration and flushing systems	20	Cowell and Apsimon (1998)
Under-floor drying systems	21	Cowell and Apsimon (1998)
Reducing crude protein content from 15% to 12%	29	Le *et al*. (2009)
Replacing $CaCO_3$ in diet with $CaCl_2$	30	van der Peet-Schwering *et al*. (1999)
Replacing $CaCO_3$ in diet with $CaSO_4$	33	van der Peet-Schwering *et al*. (1999)
Manure belt	50	Lachance *et al*. (2005)
Replacing $CaCO_3$ in diet with calcium benzoate	54	van der Peet-Schwering *et al*. (1999)
Reducing crude protein content from 22 to 13%	62	Hayes *et al*. (2004)
Manure belt and urea separation	75	Koger *et al*. (2014)
Trailing shoe spreading	28–40	Dowling *et al*. (2008)
Multi-stage scrubbers	70–100	Zhao *et al*. (2011)
Biofiltration of exhaust	64–93	Sheridan *et al*. (2002)

$CaCl_2$, calcium chloride; $CaCO_3$, calcium carbonate; $CaSO_4$, calcium sulfate.

for poultry and by 11–62% for pigs (Table 1.3). It has been shown that, although reducing crude protein in finishing pigs diets from 15% to 12% does not influence odour or greenhouse gas emissions, it does significantly reduce ammonia emissions (Le *et al*., 2009). Several further dietary methods are recommended for reducing ammonia emissions from pig farm production in addition to lowering protein content, including non-starch polysaccharides and adding acidifying salts instead of calcium carbonate ($CaCO_3$) (van der Peet-Schwering *et al*., 1999).

A reduction of 72% in ammonia emissions was observed in a Spanish broiler house by adding aluminium sulfate (alum) to bedding before introducing the flock to the house (Madrid *et al*., 2012) and a 2004 review quoted reductions of 99% (Ullman *et al*., 2004). Drying of manure in a layer house has achieved emissions as low as 0.02 kg NH_3 $bird^{-1}$ $year^{-1}$ when manure is removed daily (Groot Koerkamp, 1998a), which is equivalent to reductions of 73–86%. Manure drying techniques have also been applied to broiler farms with the intention of reducing emissions; this study enhanced internal air circulation inside the house, which displayed emissions 70% lower than the Dutch emission factor (Groot Koerkamp and Groenestein, 2008). Slurry aeration, flushing systems and under-floor drying systems have shown reductions of 20–21% in emissions from pig housing (Cowell and Apsimon, 1998). The separation of manure from urea and subsequent removal using conveyor belts has been shown to reduce ammonia emissions by 75%, which also reduces indoor concentrations (Koger *et al*., 2014). The use of multi-stage scrubbers has been shown to be more effective at reducing ammonia emissions from a pig house than single-stage scrubbers, in that emissions were reduced by between 70% and 100% (Zhao *et al*., 2011). Combinations of multiple stages were tested by this study, including the water stage, acid stage, bio-filter and bio-scrubber stages. An Irish study showed that the use of bio-filters on exhaust air could reduce emissions by 64–93%.

The BAT conclusions published by the EU in 2017 (EU, 2017) require all new/expanding IED-licensed pig and poultry farms to comply with recommendations of the decision, creating housing systems compliant with BAT-ammonia emission levels (AELs). Additionally, all existing IED-licensed farms will need to be compliant by 2021. BAT-AELs are provided for each animal type and are presented within a range; the decision provides lists of emission reduction technologies to help achieve these ranges. These emission reduction approaches include the use of filters, bio-filters, scrubbers, slurry acidification, covering manure stores and manure drying. The decision does not disclose the reduction potential of each approach. The BAT-AELs are presented for each housing type in Chapter 2 of this report and are compared with monitored emission rates from four case study farms.

In the Netherlands, a “Green Label” certificate is awarded to pig farms that reduce emissions by 40–60% compared with traditional systems. This results in the farmer being granted a lower income tax rate and a governmental guarantee that they will not be forced to rebuild their farm within 15 years (van der Peet-Schwering *et al*., 1999). The UK Environment Agency offers pig and poultry farmers membership of a “Pig and Poultry Assurance Scheme”, whereby if a farm displays “a high standard of compliance with their environmental permit” the number of inspections by the Environment Agency on the farm is reduced, resulting in a saving of £940 a year for that farm.

1.14 Summary

Ireland exceeded its NEC Directive limit for ammonia emissions in 2016, 2017 and 2018. Emissions will continue to increase without additional abatement techniques, primarily as a result of increases in livestock production under Food Wise 2025. Although pig and poultry production represent a small proportion of atmospheric ammonia emissions, concentrations near these types of intensive farms in the UK were the highest observed in previous studies. With ecological impacts recorded downwind of a poultry farm in Northern Ireland, it stands to reason that similar impacts could be expected in Ireland. All monitoring conducted indicates potential impacts, including monitoring of both lichen indicator species and concentrations. Ireland currently requires the use of critical levels or loads when conducting AA under the Habitats Directive, specifically under IED licence applications; the SCAIL-Agriculture tool is recommended for stage 1 screening, but more advanced modelling systems, such as ADMS and AERMOD, are recommended for full AAs. However, as no source-apportioned concentration model for atmospheric ammonia exists for Ireland, results from this modelling must be cautiously interpreted. The BAT conclusions, published in 2017, are applicable to all new/expanding pig and poultry farms, and from 2021 this will be the standard across all IED-licensed pig and poultry farms. There are a number of further approaches to reduce emissions from pig and poultry production; these should be considered when implementing BAT requirements on Irish farms. This study aims to identify the risk posed to Natura 2000 sites from atmospheric ammonia, inclusive of all sources, as this has not yet been addressed in Ireland. In addition, this study aims to investigate the accuracy of the EPA emission rates in pig and poultry farms by conducting detailed monitoring of emissions. The updated emission factors will then be modelled to assess the contribution to local ecological impacts from these farms.

1.15 Project Objectives

The AmmoniaN2K project aims to deliver the primary objective of quantifying and assessing the impact of ammonia from pig and poultry units on Natura 2000 sites through an innovative and effective programme of interrelated work packages culminating in a suite of targeted outputs, including the following:

- Conducting long-term ammonia emission monitoring on four case study farms for the first time in Ireland.
- Creating atmospheric ammonia dispersion models for four monitored farms to assess the effectiveness of distance screening thresholds.
- Modelling the dry deposition of ammonia from monitored farms in order to assess the potential contribution to the exceedance of critical loads.
- Identifying the potential for impacts from farms below the IED-licensed threshold.
- Identifying the number of licensed and unlicensed farms within 10 km of every Natura 2000 site.
- Incorporating licensed intensive agriculture units into a national atmospheric ammonia concentration model – Mapping Ammonia Risk on Sensitive Habitats (MARSH).
- Using the generated concentration model to identify Natura 2000 sites at risk of exceeding their critical levels.
- Monitoring atmospheric ammonia concentrations on a sample of Natura 2000 sites for the first time in Ireland.

1.16 Report Structure

This report is laid out as follows. Chapter 2 details monitoring that has taken place on four case study farms in order to consider the suitability of emission factors currently in use. Chapter 3 uses these emission factors to generate dispersion and deposition models from the four farms. Chapter 4 discusses the importance of identifying farms below the IED-licensed threshold on account of their contribution to cumulative impacts from atmospheric ammonia. Chapter 5 gauges the potential for impacts on the Natura 2000 network of designated sites from atmospheric ammonia concentration modelling (MARSH), which incorporates pig and poultry houses in addition to on-site monitoring of ammonia concentrations on Natura 2000 sites. Chapter 6 discusses the conclusions of the AmmoniaN2K project, in addition to outlining a number of recommendations. Detailed monitoring information and site-specific Natura 2000 risk information is available to download in the appendices of this report through the University College Dublin (UCD) Research Repository.

2 Monitoring Intensive Agriculture Installations

2.1 Farm Descriptions

2.1.1 Broiler Farm

The Broiler Farm comprised four houses, each of which contained *c*.32,000 birds. The farm used cycles of 30–37 days; two full cycles were monitored on this farm. This farm used wood pellets for bedding, which was removed promptly at the end of each cycle and sold for mushroom compost production. This farm operates on an all-in all-out basis, where no distinction is made between male and female birds and all are removed at the same time. No emission reduction techniques are practised on this farm.

2.1.2 Layer Farm

The Layer Farm consisted of three houses, each of which houses 42,000 birds for a full laying cycle (56–60 weeks). It also contains a naturally ventilated manure storage house, which was not monitored as part of this project. The birds are housed in enriched cages and manure is removed weekly via a conveyor belt. Manure on the conveyor belt is dried using recirculated air before its weekly removal; this is an emission reduction technique, as dry manure has lower emissions than wet manure.

2.1.3 Pig Farm 1

The following average animal numbers for Pig Farm 1 were submitted to the EPA for 2015: 414 dry/pregnant sows, 120 farrowing sows, 2100 weaners and 1800 finishers. Houses on this farm are either fully or partly slatted and are predominantly mechanically ventilated. No emission reduction techniques are practised on this farm and manure is primarily stored below the animals, though outdoor storage tanks are also used. Open outdoor storage tanks were not modelled as part of this farm, though they were present on site.

2.1.4 Pig Farm 2

The following average animal numbers for Pig Farm 2 were submitted to the EPA for 2016: 670 dry/pregnant sows, 180 farrowing sows, 4000 weaners and 2700 finishers. Houses on this farm are either fully or partly slatted and are generally mechanically ventilated. The dry/pregnant sow housing on this farm incorporates natural ventilation in addition to the mechanical vents present in some houses. No emission reduction techniques are practised on this farm and manure is primarily stored below the animals, though outdoor storage tanks are also used. Open outdoor storage tanks were not modelled as part of this farm, though they were present on site.

2.2 Protein Content

Existing research clearly associates increased ammonia emission rates with higher protein content in the diet of livestock (Ferguson, 1998; Hayes *et al*., 2004; Le *et al*., 2009; O'Shea *et al*., 2009). Introducing lower crude protein diets is often a suitable method to help lower ammonia emissions. In the broiler houses monitored, diets are spread across four stages depending on bird age; a "starter" diet will have a crude protein content of 21%, followed by "grower 1", which has its protein slightly reduced to *c*.20%. "Grower 2" will have a crude protein content of *c*.19% and "finisher" a content of 18%. Feed associated with layer production also uses varying protein content based on the age of the bird, with early-stage birds being fed 17%, followed by 16% until around week 60, and this is further reduced to 15% following week 60. The protein content across feed on both pig farms varied slightly on and between both farms, with dry/pregnant sows being fed a diet with a crude protein content of 14–15%, farrowing sows with 18%, stage 1 weaners with 20–22%, stage 2 weaners with 17–20% and finishers with 16–17%. These concentrations are broadly representative of those traditionally fed to birds/animals on Irish farms, though they may still vary from farm to farm.

2.3 Monitoring

Monitoring was undertaken on four case study farms from September 2015 to January 2018; this included one broiler farm, one layer farm and two integrated pig farms. This was prior to the introduction of

BAT-AELs on intensive agriculture in Europe. As such, emissions monitored can potentially be decreased by integrating additional measures outlined in BAT guidance (EU, 2017). In total, 17 individual animal houses were monitored, generating in excess of 100 million records, with over 90 million analysed as a part of this report. An LGR ultraportable ammonia analyser (Figure 2.1) was used in combination with an eight-inlet multiport inlet unit, allowing eight different locations to be monitored long term in sequence. This allowed multiple heights to be monitored inside both the broiler farm and the layer farm and multiple house types to be monitored on the pig farms. The air outlet from the LGR analyser was subsequently sampled by a non-dispersive infrared CO_2 sensor, namely the Senseair K30 Sensor. This allowed for the sampling of CO_2 in the same locations where ammonia was sampled. Ammonia concentrations were monitored every second, whereas CO_2 was recorded every 2–60 seconds. Each sample location was sampled for between 40 and 60 minutes, before changing to the next sampling location and continuing in sequence. The duration of the sampling periods was to ensure that the sample was representative of concentrations at the sample point and not a point within the tubing.

The system was housed inside an electrical enclosure (Figure 2.1), which was placed outside the house or houses being monitored. Low-density polyethylene (LDPE) tubing was used to link the sample locations inside the houses to the sampling unit outside the houses. The LDPE tubing was fitted with filters inside the house and the lengths of the tubing were not permitted to exceed 20 m. The electrical enclosure was fitted with a thermostatically controlled heater set at 25°C and tubing connections were insulated with elastomeric foam in order to reduce condensation inside the monitoring equipment. The temperature inside each house was continuously monitored using an Elitech portable sensor. The LGR system allowed for continuous monitoring for multiple weeks at a time. In circumstances where a house was inaccessible as a result of the limited length of tubing permitted (20 m), portable handheld sensors were used. These consisted of an iTX ammonia sampler and a Duomo Vent Check Pro handheld CO_2 sensor (which also utilises the same Senseair K30 Sensor). When this approach was taken, monitoring took place over a 24-hour period once a week for several weeks following the methodology used by Hayes *et al*. (2006a). This method was only required when monitoring weaner pigs on Pig Farm 1.

Monitoring inside broiler and layer houses allowed multiple heights inside each house to be monitored; this vertical profile of indoor concentrations of ammonia could be used to inform an animal welfare study in the future. When monitoring pigs, it was necessary to measure parameters at multiple houses at a time on account of both time constraints and the number of available sample ports on the LGR multiport inlet. For this reason, only a single monitoring point was used for each pig house, which needed to be located out of reach of the pigs and close to an outlet vent. Examples of sample locations in both pig and broiler farms are shown in Figure 2.2. Following sampling taken from each point, the system was flushed with ambient air before moving to the next location. After all the sampling locations were monitored, ambient conditions were sampled for 30 minutes. This was not intended to act as an outside ammonia sample but was done in order to flush the LGR ultraportable ammonia analyser regularly, ensuring the viability of long-term monitoring.

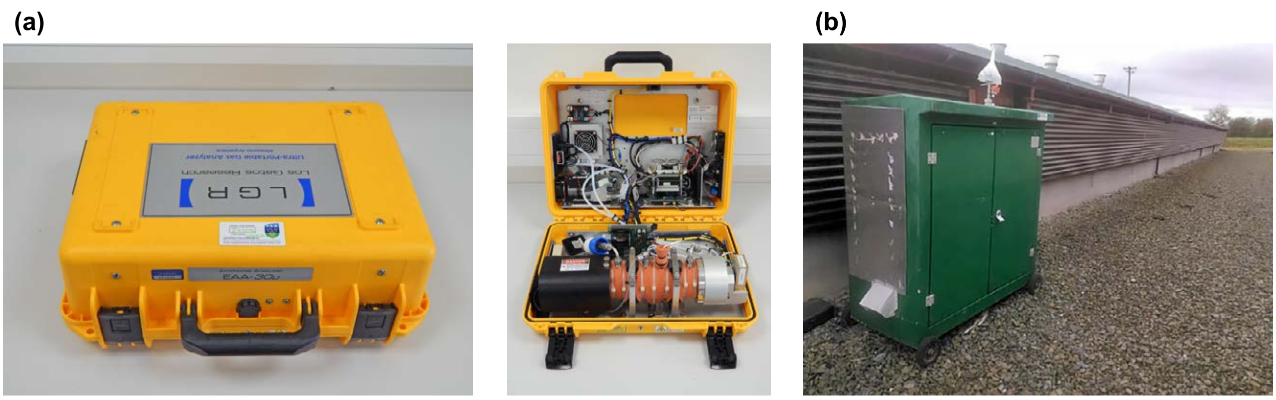

Figure 2.1. (a) LGR ultraportable ammonia analyser. (b) Electrical enclosure in operation on site.

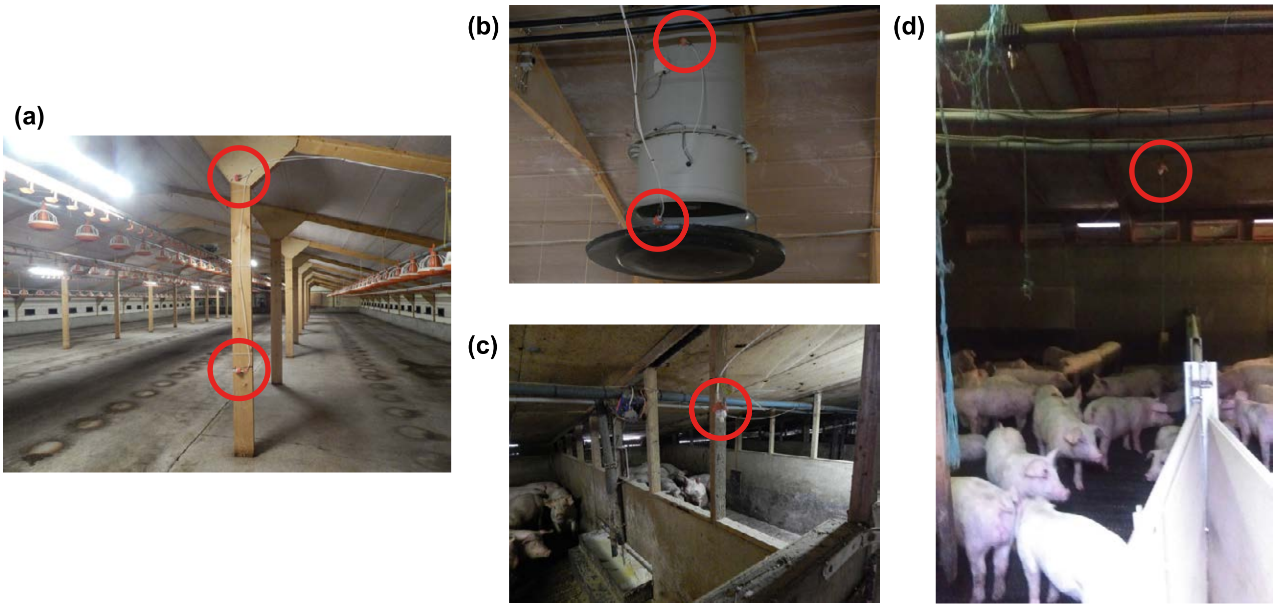

Figure 2.2. (a,b) Examples of in-house sample locations in a broiler farm, (c) a finisher house and (d) stage 2 weaner house. Sample inlets are encircled in red.

The monitoring approach used by this study generated a vast number of data, in excess of 100 million records. In order to manage this quantity of data, the ammonia and CO_2 measurements were averaged per minute and the first 10 minutes of each sample were excluded from analysis. This was essential, as the first minutes of readings were representative of concentrations within the tubing and not the sample locations. The use of 10 minutes was precautionary, as samples plateaued prior to this. The approach taken by this study allows for detailed interpretation of emission rates on a minute-by-minute basis; however, these are presented in this report as daily averages (Appendix 2) and as the average for the entire monitoring period (sections 2.6–2.8). Section 2.4 details the average emissions during the monitoring period on each farm identified in section 2.1. These are compared with standard emission factors currently in use by the EPA (EPA, 2016b) and those presented in the SCAIL-Agriculture report (Hill *et al*., 2014). In addition, the measured emissions are compared with past Irish monitoring of emissions from pig and poultry units by Hayes *et al*. (2006a,b), traditional emission factors for similar housing in the Netherlands (Starmans and van der Hoek, 2007), and the BAT-AELs (Giner Santonja *et al*., 2017). The daily emission rates are presented in Appendix 2, which are intended to represent the different times of the year in which monitoring occurred on each farm. It is important to understand that the emission rates presented are not intended to replace existing emission factors, but rather to test their accuracy over periods monitored. All emission rates and factors have been converted to kg NH_3 animal^{-1}/bird^{-1} year^{-1} in order to make direct comparison with BAT-AEL.

2.4 Ventilation Rates

When calculating emission factors, it is important to first understand the ventilation rate of the building; this can be monitored directly using anemometers or tracer gases. Both these approaches can be expensive and labour intensive; the use of CO_2 mass balance has been identified as "the only suitable technique for surveys" (Seedorf *et al*., 1998). The results from Seedorf *et al*.'s (1998) study are still used to this day as representative ventilation rates in SCAIL-Agriculture (Hill *et al*., 2014) and as such this approach is still considered suitable. It is cost-effective and allows for multiple locations to be monitored using the same equipment, accounting for both diurnal and seasonal variation. Though this approach has a typical accuracy of ±15% (Hinz and Linke, 1998; Phillips *et al*., 1998), it was deemed suitable for this study to be used as an indication of emission rates from pigs and poultry. Using the CIGR (Commission Internationale du Génie Rural or International Commission of Agricultural Engineering) guidance on using CO_2 mass balance to calculate ventilation rates (Pedersen and Sällvik, 2002), a ventilation rate for every house was calculated. This was subsequently used in combination with the indoor concentration of ammonia to calculate the ammonia emission rate.

The ventilation rates of farm buildings are intrinsically linked with their emission rates, influencing both the emission rate itself and the full extent of the dispersion plume from housing (discussed in section 2.5). The ventilation rate was calculated for all houses using CO_2 mass balance technique outlined by the CIGR (Pedersen and Sällvik, 2002). The ventilation rate per house is multiplied by the indoor concentration of ammonia, which calculates the ammonia emission rate. SCAIL-Agriculture (Hill *et al.*, 2014) reports ventilation rates in $m^3 s^{-1}$ animal/bird^{-1}; this has been converted to $m^3 h^{-1}$ animal/bird^{-1} for ease of comparison with monitored data from this study (Table 2.1). Ventilation rates presented in Table 2.1 are representative of the average ventilation per house and per animal for monitoring (see Appendix 2) conducted on each farm.

SCAIL-Agriculture reports a ventilation rate per bird of 1.51 $m^3 h^{-1}$ for broilers, which is above the range of 1.34 $m^3 h^{-1}$ observed on the monitored farm. The layer ventilation rate for the monitored farm at 3.3 $m^3 h^{-1}$ is much higher than SCAIL-Agriculture's 2.48 $m^3 h^{-1}$ for caged birds.

SCAIL-Agriculture provides a rate for sows on slats, without distinguishing between farrowing and dry/pregnant sows. Monitored sow houses exhibited a range of 45.64–100.98 $m^3 h^{-1}$ in this study; when averaged these produce a rate of 74 $m^3 h^{-1}$, comparable to SCAIL-Agriculture's 72 $m^3 h^{-1}$. The diversity of these rates highlights the importance of local monitoring and use of unique values for housing, as the average rate is not representative of houses at either end of the monitored range of ventilation rates. Weaners on slats are given a ventilation rate of 10.44 $m^3 h^{-1}$ by SCAIL-Agriculture, whereas a range of 5.85–11.28 $m^3 h^{-1}$ was observed by this study. Stage 2 weaners, or "growers", as defined by SCAIL-Agriculture, are not provided a ventilation rate in the SCAIL-Agriculture report.

Finishing pigs had a diverse array of ventilation rates within the range of 44.69–58.31 $m^3 h^{-1}$; all rates observed were higher than SCAIL-Agriculture's figure of 36 $m^3 h^{-1}$. Were the SCAIL-Agriculture figure to be used in lieu of monitored ventilation rates in dispersion models, the dispersion plume would be smaller and potentially underestimate the extent of impacts. This highlights the need for the generation of additional ventilation rates for adequate modelling of potential impacts. Using too high a rate potentially underestimates concentrations as the plume is

Table 2.1. Summary ventilation rate of houses monitored compared with SCAIL-Agriculture

Bird/animal type	House no.	Farm no.	Ventilation rate ($m^3 s^{-1}$)	Bird/animal numbers	Ventilation rate ($m^3 h^{-1}$ animal/bird^{-1})	SCAIL-Agriculture ventilation rate ($m^3 h^{-1}$ animal/bird^{-1})
Broiler	1	01	11.95	32,000	1.34	1.51
Layer	1	01	38.55	42,000	3.30	2.48
Dry/pregnant sow	1	01	4.97	392	45.64	72.00
	2	02	5.61	200	100.98	
	3	02	8.02	491	58.8	
Farrowing	1	01	0.17	8	76.50	72.00
	2	02	0.31	12	93.00	
Stage 1	1	01	0.47	155	11.28	10.44
	2	02	0.39	240	5.85	
Stage 2	1	01	1.05	155	24.39	
	2	01	1.23	155	28.57	NA
	3	02	0.79	240	11.85	
Finisher	1	01	6.67	462	51.97	36.00
	2	01	4.21	288	52.63	
	3	01	3.11	192	58.31	
	4	02	5.04	406	44.69	

NA, not applicable.

extended, whereas with too low a ventilation rate the estimated concentrations are increased but the extent is artificially decreased.

2.5 Total Farm Emissions

Total emissions for each farm were calculated using emission rates detailed in sections 2.6–2.8 in this report and are presented in Figure 2.3. The total number of reported animals for each farm in its most recent AER was used to estimate emissions from the farm for the full year. Total emissions from the broiler farm exceeded estimations using SCAIL-Agriculture rates, but these fell below the figure generated using EPA figures. Monitored layer production was on a par with estimations made using SCAIL-Agriculture rates, though slightly higher than if the EPA rates were used. Total emissions from both pig farms estimated using monitored rates exceeded estimations using both EPA and SCAIL-Agriculture emission rates. Emissions from individual monitored houses are discussed throughout sections 2.6–2.8 and compared in detail with both EPA and SCAIL-Agriculture emission rates, in addition to those from other sources (Figures 2.4–2.9).

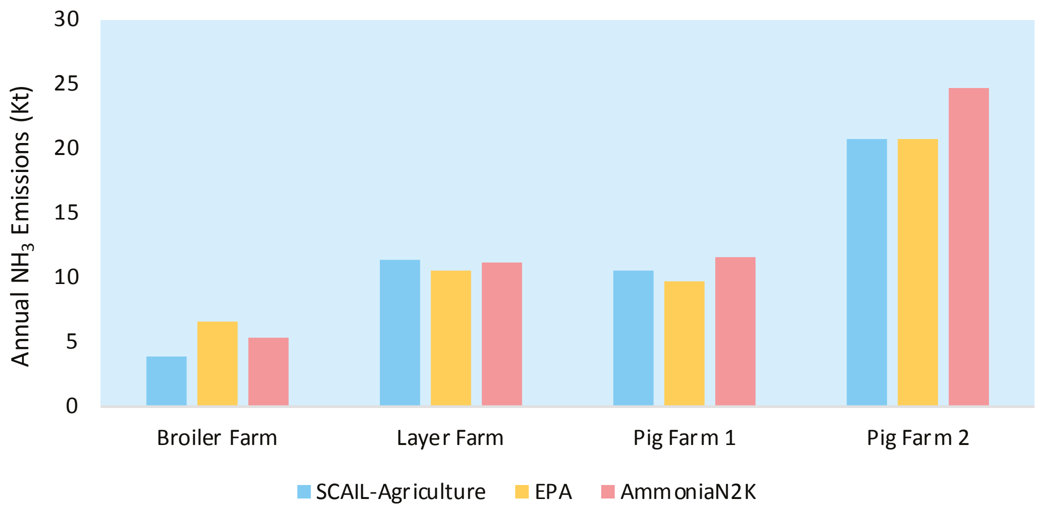

Figure 2.3. Total emissions estimated for each farm using emission rates presented in sections 2.6–2.8.

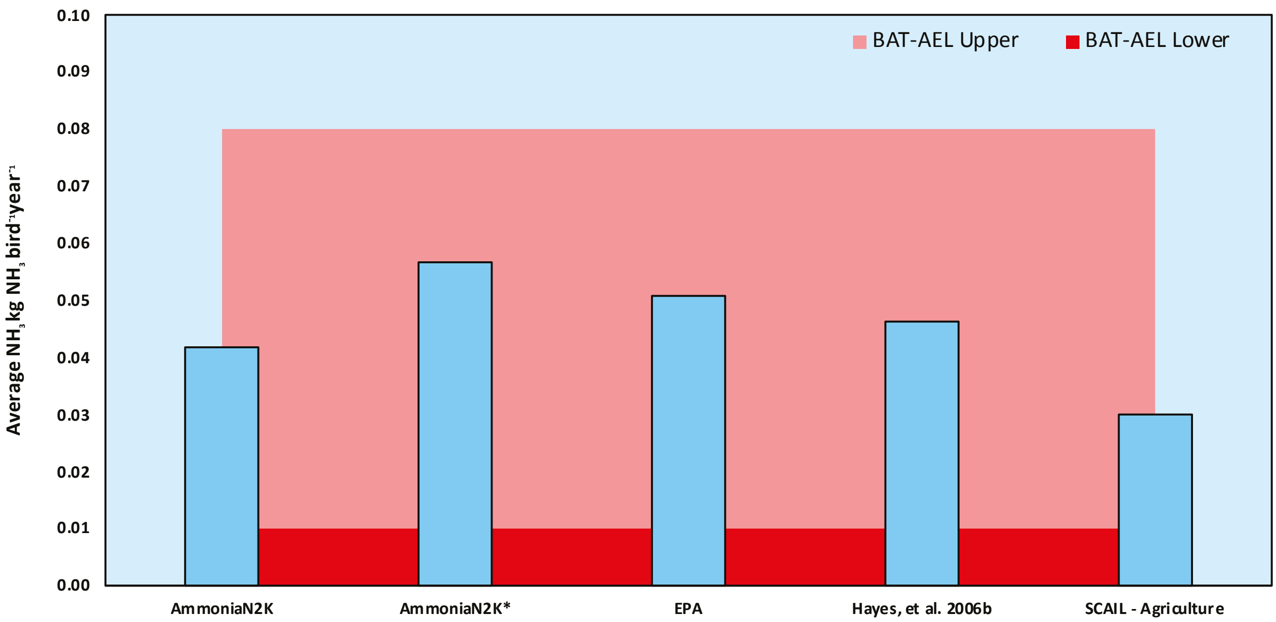

Figure 2.4. Average broiler emissions from monitored farm compared with EPA (2016b), previous Irish monitoring (Hayes *et al.*, 2006b) and SCAIL-Agriculture (Hill *et al.*, 2014) overlaying BAT-AEL range (EU, 2017). Emissions are modelled for two 37-day cycles. *Corrected for seasonal variation.

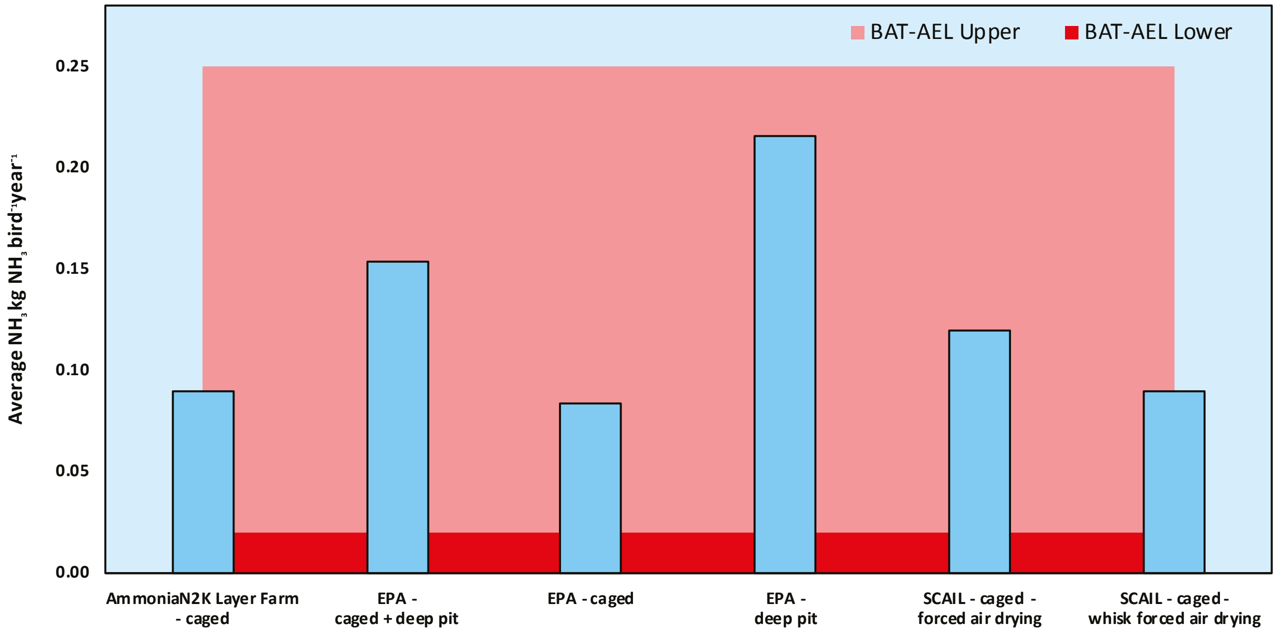

Figure 2.5. Average layer emissions from monitored farm compared with EPA (2016b) and SCAIL-Agriculture (Hill *et al*., 2014) overlaying the BAT-AEL range (EU, 2017).

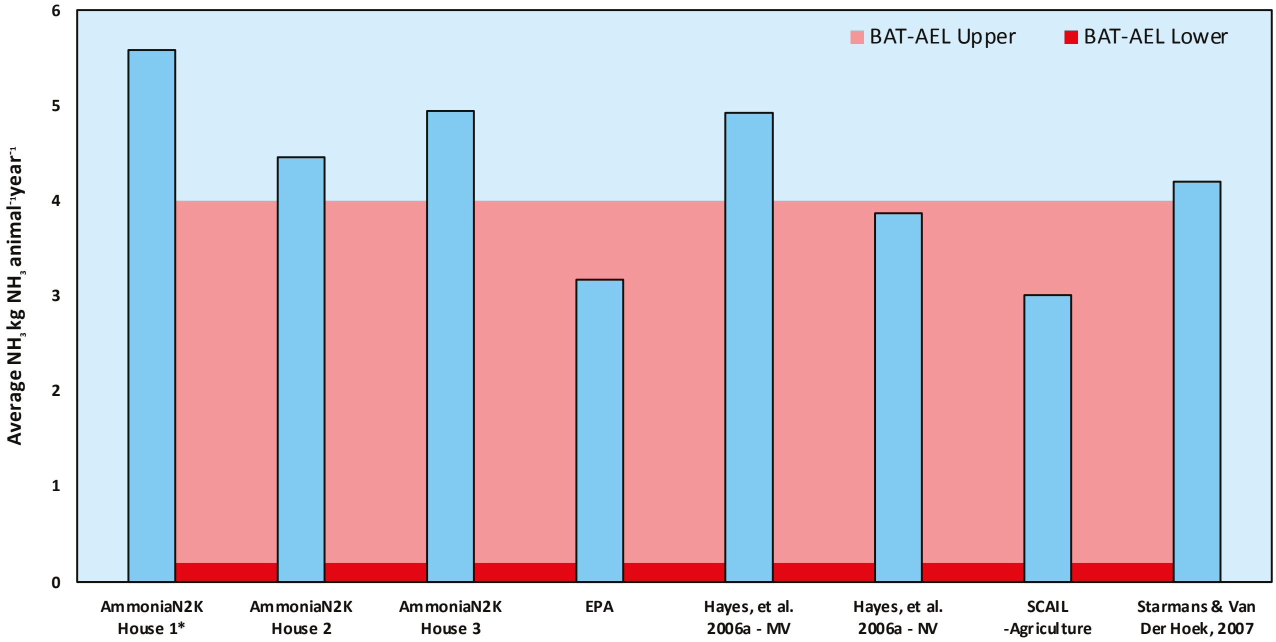

Figure 2.6. Average dry/pregnant sow emissions from three monitored houses compared with EPA (2016b), previous Irish monitoring (Hayes *et al*. 2006a), SCAIL-Agriculture (Hill *et al*., 2014) and rates for similar housing in the Netherlands (Starmans and van der Hoek, 2007), overlaying BAT-AEL range (EU, 2017). *Corrected for seasonal variation. MV, mechanical ventilated; NV, naturally ventilated.

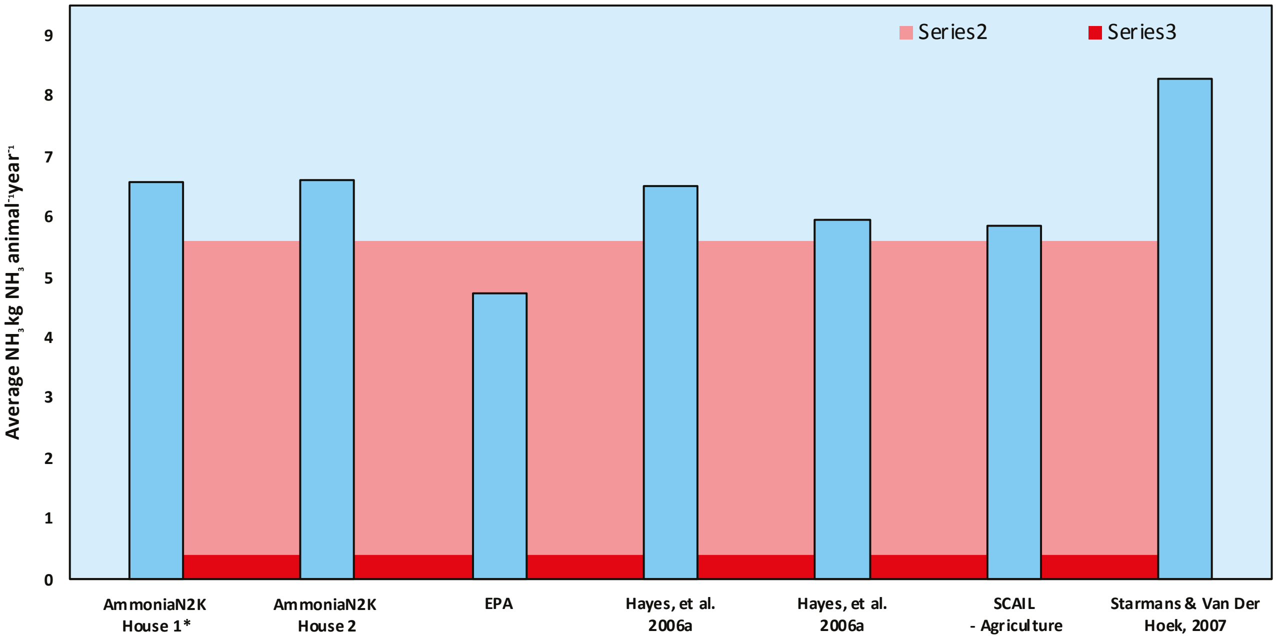

Figure 2.7. Average farrowing sow emissions from two monitored houses compared with EPA (EPA, 2016), previous Irish monitoring (Hayes *et al*., 2006a), SCAIL-Agriculture (Hill *et al*., 2014) and rates for similar housing in the Netherlands (Starmans and van der Hoek, 2007) overlaying BAT-AEL range (EU, 2017). *Corrected for seasonal variation.

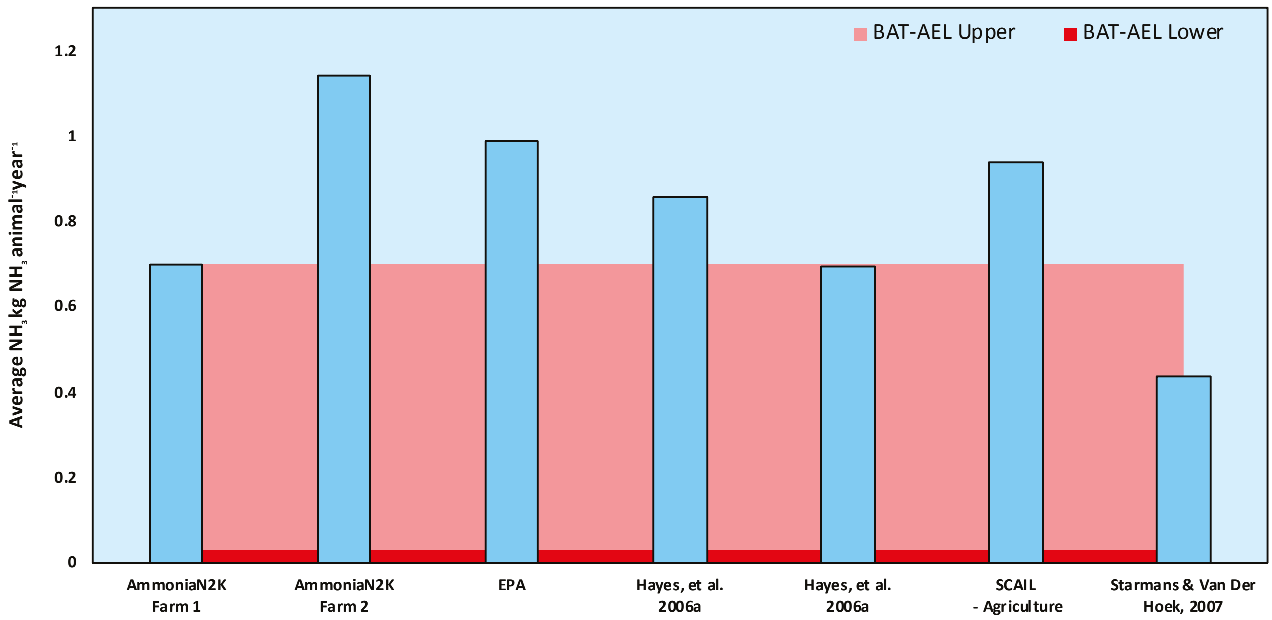

Figure 2.8. Average weaner emissions from two farms (inclusive of stages 1 and 2) compared with EPA (2016b), previous Irish monitoring (Hayes *et al*., 2006a), SCAIL-Agriculture (Hill *et al*., 2014) and rates for similar housing in the Netherlands (Starmans and van der Hoek, 2007) overlaying BAT-AEL range (EU, 2017).

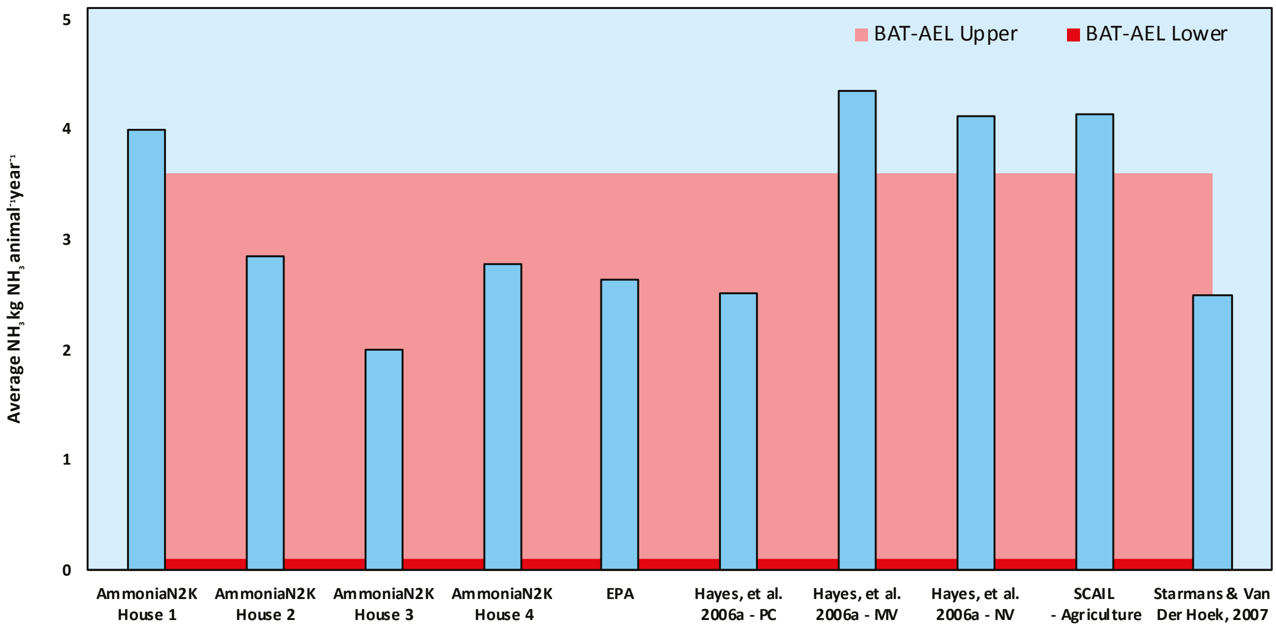

Figure 2.9. Average finisher pig emissions from four monitored houses compared with EPA (2016b), previous Irish monitoring (Hayes *et al.*, 2006a), SCAIL-Agriculture (Hill *et al.*, 2014) and rates for similar housing in the Netherlands (Starmans and van der Hoek, 2007) overlaying BAT-AEL range (EU, 2017). MV, mechanical ventilated; NV, naturally ventilated; PC, porous ceiling.

2.6 Broiler Emission Monitoring

Broiler production in Ireland generally utilises houses with a capacity of 32,000–34,000 birds for between 30 and 37 days. Monitoring of ammonia emissions from broiler production took place on a farm located in an area with multiple nearby sources of ammonia, including additional hotspot sources of ammonia. Two full cycles were monitored on the broiler farm (33 and 37 days). Emissions for two full 37-day cycles were estimated based on proportional increases over the final 4 days of the cycle. Emissions are presented in kg NH_3 bird^{-1} year^{-1}, based on 231 production days (EPA, 2016b).

The average monitored emission rate for the house on Broiler Farm 1 was 0.04 kg NH_3 bird^{-1} year^{-1} (Figure 2.4), which is lower than the current EPA emission factor of 0.05 kg NH_3 bird^{-1} year^{-1} (EPA, 2016b). When modelled to include two full 37-day cycles, emissions increased to 0.06 kg NH_3 bird^{-1} year^{-1}, as the final 4 days of a cycle are likely to have the highest emission rates. This is because of the growth of broilers throughout their cycle; as birds get older and larger, more manure accumulates and the emissions increase. Both the modelled and monitored emission rates should be interpreted with caution, as the cycle with the lower rate ended prematurely on account of a market request and the modelled rate provided is an estimate.

All monitored rates, including the 0.05 kg NH_3 bird^{-1} year^{-1} monitored by Hayes *et al.* (2006b), fall below the BAT-AELs of 0.08 kg NH_3 bird^{-1} year^{-1}. This limit has been set for 2.5-kg birds, with the maximum weights of birds in the two cycles monitored being 1.84 and 2.21 kg. If the duration of the production cycle was increased to allow for additional growth, it may become more difficult to fall within the upper AEL. All rates are much higher than the lower AEL set under BAT, highlighting that reduction approaches have not been applied on the monitored farm or represented in EPA and SCAIL-Agriculture emission factors. The EPA emission factor was calculated based on a bird weight of 2 kg (B. Hyde, EPA, 26 February 2014, personal communication) using UK emission rates; 2 kg is the finishing weight of broilers, not their average weight, and hence is an overestimate of potential emissions despite similarity to the modelled emission rate.

2.7 Layer Emission Monitoring

Layer hens are raised throughout the year over deep litter manure pits or they have the manure removed from the house using conveyor belts under the birds. A modern layer farm that uses enriched cages, removing manure once a week utilising forced air drying of manure, was monitored as part of the AmmoniaN2K project. BAT guidance (European Union, 2017) highlights a range of 0.02–0.08 kg NH_3 bird^{-1} year^{-1}, which is extended to an upper limit of 0.25 kg NH_3 bird^{-1} year^{-1} if manure drying is applied within the production system. The monitored farm utilises recirculated warm air to dry manure on conveyor belts, which remove the manure weekly.

The emission factor currently used by the EPA (B. Hyde, EPA, 26 February 2014, personal communication) was sourced from the figure reported in 2004 in the UK for layers in cages (Misselbrook *et al*., 2004). This figure averaged the UK's emission factor layers housed over manure belts and deep pits. When corrected to exclude deep pit, and to correspond with the weight of the birds monitored, the daily emission factor was 0.08 kg NH_3 bird^{-1} year^{-1}, which is slightly lower than the average emissions of the monitored layer farm in this study at 0.09 kg NH_3 bird^{-1} year^{-1} (Figure 2.5). By altering the same equation used by the EPA to calculate the emission layer emission rate based on the 2004 UK inventory (Misselbrook *et al*., 2004), a potential emission rate of 0.22 kg NH_3 bird^{-1} year^{-1} can be estimated for layers within deep pit production systems.

SCAIL-Agriculture emission factors for caged layers with weekly manure removal are presented with two different methods of manure drying, namely forced air and whisk-forced air drying. The non-whisk-forced air drying approach is most similar to that in the monitored house. The figure presented for forced air drying (0.12 kg NH_3 bird^{-1} year^{-1}) is considerably higher than both the monitored and the EPA caged emission rates, whereas whisk-forced air drying value is much closer, at 0.09 kg NH_3 bird^{-1} year^{-1}. The manure-drying system is hence vitally important to reduce emissions, with the system utilised in the monitored farm producing the same rate as the whisk-forced air drying system identified in the SCAIL-Agriculture report.

2.8 Pig Emission Monitoring

2.8.1 Dry/pregnant sow emission monitoring

Dry/pregnant sows are generally housed over fully slatted floors, underneath which manure is stored. The EPA currently reports an emission factor of 3.17 kg NH_3 animal^{-1} year^{-1} for dry sows, which is slightly higher than the SCAIL-Agriculture's 3.01 kg NH_3 animal^{-1} year^{-1}. Past monitoring in Ireland showed a difference in emissions in mechanically ventilated dry sow housing and naturally ventilated housing (Hayes *et al*., 2006a), which were 4.93 and 3.87 kg NH_3 animal^{-1} year^{-1}, respectively. The AmmoniaN2K project monitored three dry/pregnant sow houses across two farms, each with varying ventilation systems and stocking densities. A fully mechanically ventilated house (House 1) had the highest emission rate, at 5.58 kg NH_3 animal^{-1} year^{-1} (Figure 2.6), when compared with two houses that use a combination of natural and mechanical ventilation (Houses 2 and 3). Incomplete monitoring on House 1 required the rate to be artificially corrected to account for seasonal diversity of emissions. House 2, with an average emission rate of 4.46 kg NH_3 animal^{-1} year^{-1}, is slightly higher than the emission factor for traditional housing in the Netherlands, at 4.2 kg NH_3 animal^{-1} year^{-1}. House 3's average emission rate of 4.94 kg NH_3 animal^{-1} year^{-1} is slightly higher than that monitored in the mechanically ventilated house by Hayes *et al*. (2006a) at 4.93 kg NH_3 animal^{-1} year^{-1}. The only rates that fall below the upper BAT-AEL are those used by the EPA and SCAIL-Agriculture and the naturally ventilated house in Hayes *et al*. (2006a). All rates monitored on both farms in the current study, in addition to the mechanically ventilated farm in Hayes *et al*. (2006a) and those for the same housing type in the Netherlands (Starmans and van der Hoek, 2007), exceed the upper limit set under BAT. All rates are significantly higher than the lower BAT-AEL, highlighting the need for further emission reduction strategies in dry/pregnant sow housing. The past and current monitoring on Irish farms suggests that both the EPA and SCAIL-Agriculture rates were, in this case, an underestimate of emission rates. This is an important distinction to make, as emission factors used are below the upper BAT-AEL, whereas monitored rates are above it.

2.8.2 Farrowing sow emission monitoring

Farrowing sows are generally housed over fully slatted floors and can be either mechanically or naturally ventilated. Both monitored houses were naturally ventilated and they were identical in structure and layout. The EPA currently uses an emission factor of 4.72 kg NH_3 animal^{-1} year^{-1}, whereas the SCAIL-Agriculture and past Irish monitoring suggest an emission factor of 5.84–6.50 kg NH_3 animal^{-1} year^{-1}, which may be more relevant.

Farrowing houses monitored by the AmmoniaN2K project displayed emission rates of 6.57–6.61 kg NH_3 animal^{-1} year^{-1} (Figure 2.7) (House 1 was corrected to account for seasonal variation). Similar housing in the Netherlands has a much higher rate, at 8.30 kg NH_3 animal^{-1} year^{-1}, which may be because of subtly different practices in raising farrowing sows. Regardless, every rate presented in Figure 2.7 is above the upper BAT-AEL, with the exception of the rate used by the EPA. This indicates that the rate used by the EPA may be an underestimate and this highlights that emission reduction strategies are required in order to ensure compliance with BAT for farrowing sow housing.

2.8.3 *Weaner emission monitoring*

Weaners are generally housed on slatted floors, with some level of mechanical ventilation. The EPA does not differentiate between stage 1 and stage 2 weaners in its AER/PRTR guidance, though both are housed separately. In total, five weaner houses were monitored by the AmmoniaN2K project, with Farm 1 splitting its weaners into three growth stages and Farm 2 retaining standard stage 1 to stage 2. The weight classifications of these stages varied between the farms, which invariably influences the emissions associated with each stage. For ease of interpretation, all weaner stages for each farm are averaged and presented in Table 2.2. The monitoring approach for both farms varied and the results are not directly comparable; whereas on Farm 1 iTX ammonia and Duomo CO_2 sensors were used, on Farm 2 LGR and K30 sensors were used. This was on account of the inaccessibility of buildings on Farm 1 to sensor equipment.

Averaging monitored stage 1 and stage 2 emissions allows for direct comparison with the EPA's emission rate and BAT-AEL's for weaners. Pig Farm 1, where the weaners were divided into three stages, seems to have reduced the overall average emission rate to 0.7 kg NH_3 animal^{-1} year^{-1} when compared with Farm 2's 1.14 kg NH_3 animal^{-1} year^{-1} (Figure 2.8). Farm 1, a farm monitored by Hayes *et al*. (2006a) with 0.69 kg NH_3 animal^{-1} year^{-1} and the similar house type in the Netherlands with 0.44 kg NH_3 animal^{-1} year^{-1} (Starmans and van der Hoek, 2007) are the only three rates shown in Figure 2.8 that comply with the upper BAT-AEL. The SCAIL-Agriculture emissions rate is the average of weaners and growers as identified in the SCAIL-Agriculture report (Hill *et al*., 2014), which, with 0.94 kg NH_3 animal^{-1} year^{-1}, is broadly similar to the EPA rate of 0.99 kg NH_3 animal^{-1} year^{-1}, and both are above the upper BAT-AEL. The diversity in emission factors and rates is probably the result of the classification of weaners at different stages on different farms. However, this highlights the importance of emission reduction strategies for weaner production, on account of both figures used in guidance and monitored rates exceeding the upper BAT-AEL.

2.8.4 *Finisher emission monitoring*

Finishing pigs are primarily housed over fully slatted floors, though they can be exposed to a variety of ventilation types. The EPA currently uses an emission factor of 2.64 kg NH_3 animal^{-1} year^{-1} (EPA, 2016b), which is lower than SCAIL-Agriculture's emission factor of 4.14 kg NH_3 animal^{-1} year^{-1}. Both rates are intended to represent the same type of housing; one is below the BAT-AEL upper limits of 3.6 kg NH_3 animal^{-1} year^{-1}, while the other exceeds it. Monitoring on Houses 2, 3 and 4 all generated emission rates below the upper BAT-AEL; the only monitored house that exceeded this limit was the newest house, which was built after 2000 (Figure 2.9).

Table 2.2. Summary weights of different weaner stages

	Farm	House	Animal number	Start weight (kg)
Stage 1	1	1	150	12.9
Weaner	2	2	240	15.5
Stage 2	1	1	155	26.05
Weaner	1	2	155	40.9
	2	3	240	37.5

The newer house, which was equipped with a modern ventilation system, showed a higher ventilation rate (Table 2.1), accompanied by a higher emission rate.

The EPA emission factor is based on the average emission rate from a number of Irish studies conducted between 2004 and 2009 (B. Hyde, EPA, 26 February 2014, personal communication); these studies focused on dietary studies of emissions and were primarily conducted on a university farm. When averaged they produce a rate of 2.64 kg NH_3 animal^{-1} year^{-1}, which is significantly lower than monitoring conducted in active mechanically and naturally ventilated finisher houses of 4.34 and 4.12 kg NH_3 animal^{-1} year^{-1}, respectively (Hayes *et al*., 2006a). The ventilation type for House 3 was similar to the porous ceiling house monitored by Hayes *et al*. (2006a), though the emission rate is lower at 2.00 kg NH_3 animal^{-1} year^{-1} than Hayes's 2.52 kg NH_3 animal^{-1} year^{-1}.

Though all four monitored houses were mechanically ventilated, other slight variations resulted in different ventilation and emission rates. House 2 was built in the 1990s with an emission rate of 2.85 kg NH_3 animal^{-1} year^{-1}, which was higher than that of Houses 3 and 4 built in the 1970s, at 2.00 and 2.77 kg NH_3 animal^{-1} year^{-1}, respectively. The older houses are broadly similar to the same housing type in the Netherlands, with an emission rate of 2.50 kg NH_3 animal^{-1} year^{-1}. It appears, based on monitoring of these four houses, that the older the finisher house, the lower the emissions. This statement would require additional monitoring in order to show this effect statistically.

3 Atmospheric Dispersion Models

There are many atmospheric dispersion models available (e.g. Industrial Source Complex – ISC; ADMS; AERMOD; CALPUFF; The Air Pollution Model – TAPM), many of which are based on a plume dispersion approach and some of the more advanced ones are based on a puff model. Depending on the way the models are set up with the available input data, different models can generate almost identical results, e.g. a comparison of a plume model (ISC3) and an advanced puff model (CALPUFF) for the prediction of odour concentrations around a commercial pig unit provided similar results (Curran *et al.*, 2007). SCAIL-Agriculture is a screening tool that is available for use in both the UK and Ireland for assessing the impact from livestock units on protected areas, primarily SACs and SPAs (Hill *et al.*, 2014). The model utilises the US EPA's AERMOD dispersion model to provide an estimate of atmospheric ammonia concentrations and deposition on sensitive habitats from an intensive livestock unit, storage area or spreading technique.

The Environment Agency recommends modelling approaches for both mechanically and naturally ventilated buildings. Buildings with individual mechanical roof vents should be modelled as a series of elevated point sources, whereas naturally ventilated sheds should be modelled as either volume or linear sources depending on the building design (Environment Agency, 2010). This presents a problem when calculating the ventilation rate of individual fans for mechanically ventilated buildings, as the ventilation rate per fan is difficult to determine without direct monitoring. Indirect methods, such as CO_2 mass balance, used by this study present a ventilation rate per building, not per fan. SCAIL-Agriculture also utilises a ventilation for the entire building by using a ventilation rate per animal and recommends using a single point source for the building by summing fan diameter of all fans, rather than just one (Hill *et al.*, 2014). The AmmoniaN2K project adopted an approach similar to that used by SCAIL-Agriculture to model dispersion of atmospheric ammonia from monitored pig and poultry farms. Here, each individual house was modelled using AERMOD as a single point source and the output diameter was calculated based on the "total effective diameter" of the house. The total effective diameter was obtained by summing the area of all exhausts and determining the diameter of the total area as if it were a single circular outlet. This was applied to both mechanically and naturally ventilated buildings as exact measurements were obtained from all farms. The emission and ventilation rates presented in Chapter 2 of this report were used in combination with local meteorological data. In line with the Environment Agency's guidelines to monitor dispersion for the 5 most recent years separately (Environment Agency, 2010), the dispersion of each house was modelled for every year from 2013 to 2017.

3.1 Meteorological Data

Meteorological data for all monitored sites were obtained for 2013–2017 from the nearest Met Éireann synoptic meteorological stations. These sites record the following data required to run AERMOD on an hourly basis: temperature, relative humidity, mean sea level pressure, wind direction, wind speed and rainfall. In addition to these parameters, AERMOD requires the inclusion of cloud cover and ceiling height. The closest meteorological station that records these parameters on an hourly basis is Dublin Airport. As such, cloud cover and ceiling height recorded at Dublin Airport were used in conjunction with data from Ballyhaise and Dunsany synoptic meteorological stations.

3.2 Atmospheric Ammonia Dispersion and Deposition Modelling

Using the data collected during monitoring of each farm, and the 5 years of local meteorological data, AERMOD was used to create five dispersion models for each farm, one for every year between 2013 and 2017. This was done to clarify meteorological conditions that had maximum and minimum dispersion potential. This is an important consideration for modelling potential contributions to impacts, because if a model had been created only for the year with greatest dispersion potential the local concentrations could have potentially been underestimated. Likewise, if a model had been created for only the year with minimum dispersion potential, the maximum extent of ammonia dispersion could have potentially been underestimated. This modelling showed that 2017 had the maximum dispersion potential of those 5 years, with 2015 having the smallest dispersion extent. Modelled extents for 0.01 $\mu g\,NH_3\,m^{-3}$, 0.03 $\mu g\,NH_3\,m^{-3}$, 0.04 $\mu g\,NH_3\,m^{-3}$, 0.12 $\mu g\,NH_3\,m^{-3}$, 1 $\mu g\,NH_3\,m^{-3}$, 3 $\mu g\,NH_3\,m^{-3}$, 5 $\mu g\,NH_3\,m^{-3}$ and 8 $\mu g\,NH_3\,m^{-3}$ were selected to be displayed in AERMOD's output contours. The dispersion extents summarised in Table 3.1 solely identify the ammonia process contributions from housing and do not include contributions from outdoor slurry storage or ambient concentrations. Table 3.1 presents the maximum distance downwind for each concentration modelled from the centre of each farm. Similar to SCAIL-Agriculture, these models do not account for the depletion, deposition or conversion of atmospheric ammonia from the farms. This is in line with the precautionary principle, on account of the uncertainty regarding ammonia loss through deposition and conversion, and mimics models generated by SCAIL-Agriculture. This leads to an overestimation of concentrations on the plume border by *c.*10% (Hill *et al.*, 2014).

Once ammonia is released into the atmosphere, it is inevitably deposited through either wet (rain) or dry deposition. Dry deposition refers to when a pollutant settles to the ground naturally from the atmosphere or when it is absorbed by plant tissues. The SCAIL-Agriculture tool excludes wet deposition from its calculations because of "the dominance of local ammonia dry deposition" (Hill *et al.*, 2014). Hence, as part of the AmmoniaN2K project, dry deposition of emissions from pig and poultry farms was calculated and wet deposition was not. SCAIL-Agriculture estimates an overestimation of dry deposition by *c.*10% because it does not incorporate chemical conversion or dry depletion (Hill *et al.*, 2014), which is reasonable presuming the precautionary principle required under the Habitats Directive. Deposition velocities for woodlands (0.03 $m\,s^{-1}$) and other habitats (0.02 $m\,s^{-1}$) were used as listed in the SCAIL-Agriculture report to estimate the dry deposition of modelled concentrations of ammonia from the monitored farms. As dry deposition depends on the surface roughness of surrounding habitats, it will inevitably have a high variability between sites with different neighbouring habitats. As a result, the distance at which deposition values occur is likely to vary significantly between different farms based on proximal habitat types; for example, deposition is higher on woodlands than on grasslands and urban areas.

Table 3.1. Summary of ammonia concentrations and dry deposition from dispersion modelling and their maximum plume extent from modelled pig and poultry farms for 2015 and 2017

Ammonia concentration ($\mu g\,NH_3\,m^{-3}$)	Dry deposition ($kg\,N\,ha^{-1}\,year^{-1}$)		Maximum plume extent (m)			
	Woodland	Other habitats	Broiler Farm	Layer Farm	Pig Farm 1	Pig Farm 2
0.01	0.08	0.05	32,594	28,573	30,470	50,938
0.03	0.2	0.16	14,648	7079	13,280	24,727
0.04	0.3	0.21	10,380	6541	10,432	20,110
0.06	0.5	0.3	4024	3688	7485	15628
0.12	0.9	0.6	2218	2054	4430	7645
1	7.8	5.2	432	399	800	1685
3	23.4	15.6	187	172	389	684
5	39	26	146	129	0	581
8	62.3	41.6	0	93	0	442

Note: Broiler Farm – 134,000 birds; Layer Farm – 126,000 birds; Pig Farm 1 – 420 sows; Pig Farm 2 – 670 sows.

3.2.1 Broiler Farm dispersion model

Modelling was conducted for all houses on the farm, as all houses held the same number of animals as the monitored house and had identical ventilation and heating systems. Dispersion models are visualised by contours presented in Figure 3.1, which has been summarised in Table 3.1. The maximum distance downwind from the broiler house for a concentration of 5 µg NH_3 m^{-3} was 146 m, at which point – including the maximum ambient concentrations of 2.96–3.21 µg NH_3 m^{-3} – the concentrations would exceed 8 µg NH_3 m^{-3}. This is the same concentration that elicited severe negative ecological effects on Moninea Bog in Northern Ireland (Sutton *et al.*, 2011). The process contribution exceeds critical levels of 3 and 1 µg NH_3 m^{-3} at 187 and 432 m from the centre of the farm, respectively, without inclusion of other sources of ammonia. Thresholds for cumulative impacts and requirement of detailed dispersion modelling in Ireland and the UK are set at 4% and 1% (depending on regulatory body) of critical levels, hence contours for 0.12 µg NH_3 m^{-3} (4% of 3 µg NH_3 m^{-3}), 0.04 µg NH_3 m^{-3} (4% of 1 µg NH_3 m^{-3}), 0.03 µg NH_3 m^{-3} (1% of 3 µg NH_3 m^{-3}) and 0.01 µg NH_3 m^{-3} (1% of 1 µg NH_3 m^{-3}) were generated. These concentrations were exceeded within 2.2 km, 10.4 km, 14.6 km and 32.6 km from the centre of the farm. The greater the dispersion plume, the greater the potential for cumulative impacts of atmospheric ammonia, which has not yet been modelled in Ireland. If an area has a large number of such farms, the potential cumulative impact could be significant.

3.2.2 Layer Farm dispersion model

Similar to the Broiler Farm, dispersion for the layer house was modelled for all three houses, as all houses were identical to the one monitored. Dispersion contours are presented in Figure 3.2 and they are summarised in Table 3.1. The highest concentration modelled in the Layer Farm was 8 µg NH_3 m^{-3}, followed by 5 µg NH_3 m^{-3} within 129 m of the farm centre; including the maximum monitored ambient concentration here would elicit severe impacts, as observed in Moninea Bog (Sutton *et al.*, 2011). Critical levels of 3 and 1 µg NH_3 m^{-3} were exceeded within 172 and 399 m, respectively, from the process contribution of the farm alone. Thresholds for cumulative impacts and requirement of detailed dispersion modelling in Ireland and the UK are set at 4% and 1% (depending on regulatory body) of critical levels, hence contours for 0.12 µg NH_3 m^{-3} (4% of 3 µg NH_3 m^{-3}), 0.04 µg NH_3 m^{-3} (4% of 1 µg NH_3 m^{-3}), 0.03 µg NH_3 m^{-3} (1% of 3 µg NH_3 m^{-3}) and 0.01 µg NH_3 m^{-3} (1% of 1 µg NH_3 m^{-3}) were generated. These concentrations were exceeded within 2 km, 6.5 km, 7.1 km and 28.6 km from the centre of the farm. Despite the much higher ventilation rate of the building (see Table 2.1), the effective diameter was much greater than the monitored Broiler Farm and pig farms, reducing its exit velocity.

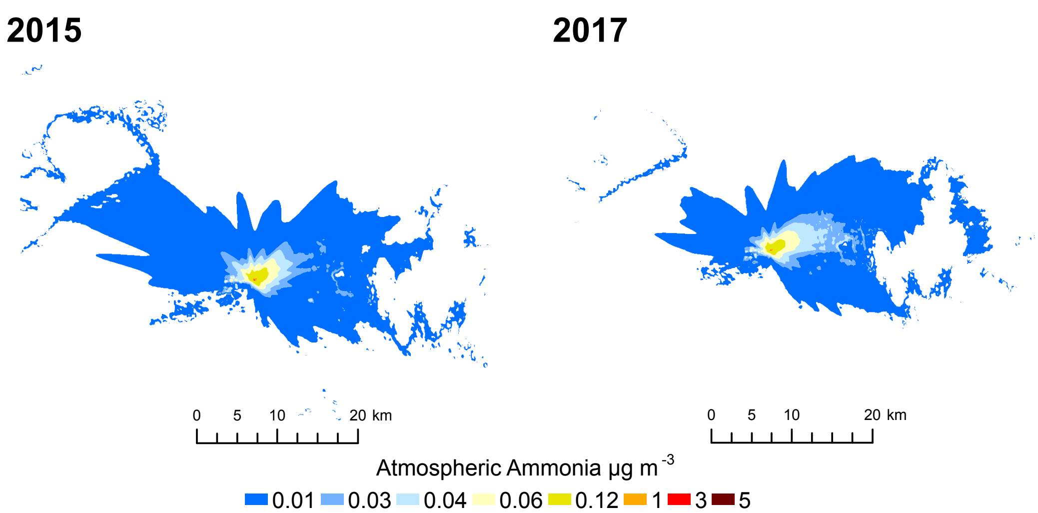

Figure 3.1. Modelled dispersion of ammonia from the monitored Broiler Farm in 2015 and 2017.

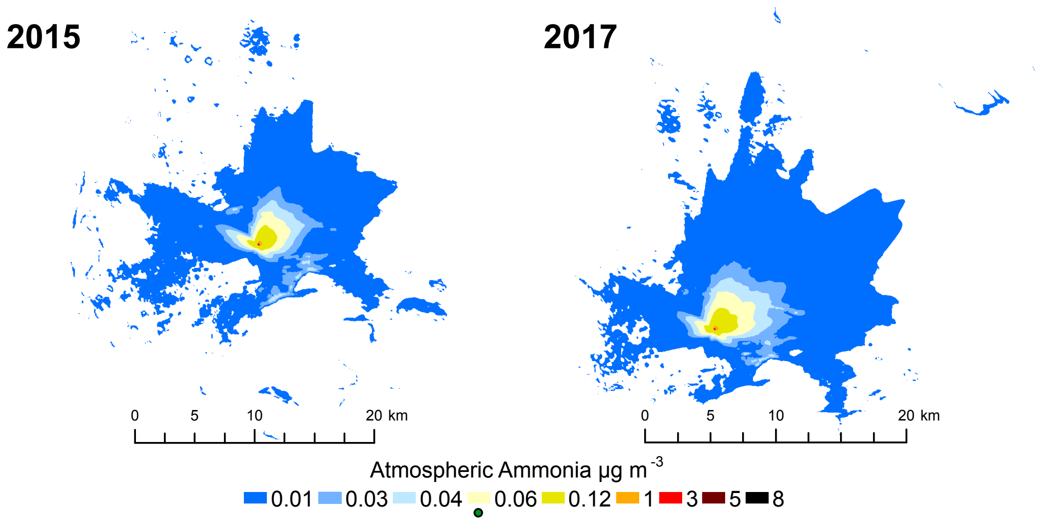

Figure 3.2. Modelled dispersion of ammonia from the monitored Layer Farm in 2015 and 2017.

3.2.3 Pig farm dispersion models

The layout of the two pig farms was much more complex compared with the broiler and layer farms, with numerous smaller houses occupied by pigs at different life stages. Detailed maps of each farm were created, and for houses not monitored the values from the most similar house monitored were applied on a per animal basis. The total number of animals varies across all Irish pig farms; Figure 3.3 presents the total number of licensed dry/pregnant sows on all licensed farms where counted (an indicator of the size of farm).

Dispersion contours are presented in Figures 3.4 and 3.5, which are summarised in Table 3.1. For Pig Farm 1, the highest concentration modelled from the farm was 3 µg NH_3 m^{-3} within 400 m of the farm centre, an exceedance of the critical level for higher plants. Critical levels of 1 µg NH_3 m^{-3} were exceeded within 800 m, similarly from the process contribution of the farm alone. Thresholds for cumulative impacts and requirement of detailed dispersion modelling in Ireland and the UK are set at 4% and 1% (depending on regulatory body) of critical levels, hence contours for 0.12 µg NH_3 m^{-3} (4% of 3 µg NH_3 m^{-3}), 0.04 µg NH_3 m^{-3} (4% of 1 µg NH_3 m^{-3}), 0.03 µg NH_3 m^{-3} (1% of 3 µg NH_3 m^{-3}) and 0.01 µg NH_3 m^{-3} (1% of 1 µg NH_3 m^{-3}) were generated. These concentrations were exceeded within 4.4 km, 10.4 km, 13.3 km and 30.5 km from the centre of the farm.

For Pig Farm 2, concentrations comparable to severe impacts observed on Moninea Bog in Northern Ireland (Sutton *et al*., 2011) occur within 581 m from the centre of the farm. Critical levels of 3 µg NH_3 m^{-3} and 1 µg NH_3 m^{-3} were exceeded within 684 m and 1685 m, respectively, from the process contribution of the farm alone. Thresholds for cumulative impacts and requirement of detailed dispersion modelling in Ireland and the UK are set at 4 and 1% (depending on regulatory body) of critical levels, hence contours for 0.12 µg NH_3 m^{-3} (4% of 3 µg NH_3 m^{-3}), 0.04 µg NH_3 m^{-3} (4% of 1 µg NH_3 m^{-3}), 0.03 µg NH_3 m^{-3} (1% of 3 µg NH_3 m^{-3}) and 0.01 µg NH_3 m^{-3} (1% of 1 µg NH_3 m^{-3}) were generated. These concentrations were exceeded within 7.6 km, 20.1 km, 24.7 km and 50.9 km from the centre of the farm.

Ambient concentrations have been monitored twice across Ireland, indicating ranges of 0.48–2.96 µg NH^3 m^{-3} (Doyle *et al*., 2017) and 0.18–3.21 µg NH^3 m^{-3} (de Kluizenaar and Farrell, 2000). This monitoring intentionally excluded monitoring near hotspot sources such as pig and poultry farms. Hence, the modelled concentrations added to these values is most indicative of potential impacts. Both critical levels are exceeded by the highest recorded ambient concentration, using this concentration as a worst-case scenario, 8 µg NH_3 m^{-3} (which is the concentration that caused severe impacts on Moninea Bog; Sutton *et al*., 2011) is exceeded within 146 m, 129 m and 581 m of the Broiler Farm, Layer Farm and Pig Farm 2, respectively.

To summarise, contributions to ammonia concentrations exceeded 1 µg NH_3 m^{-3} within 432 m, 399 m, 800 m and 1685 m of the Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively.

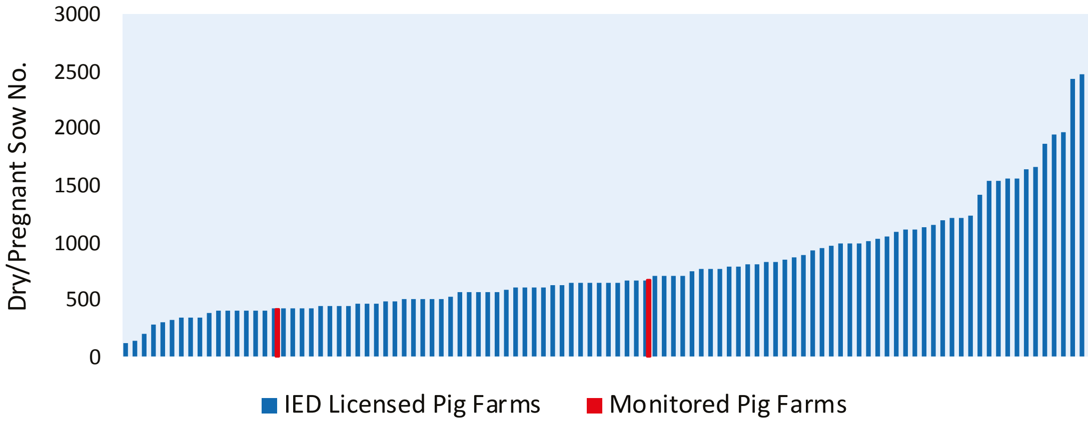

Figure 3.3. Total number of dry/pregnant sows recorded within each licensed pig farms based on a review of each individual application from EPA (2017).

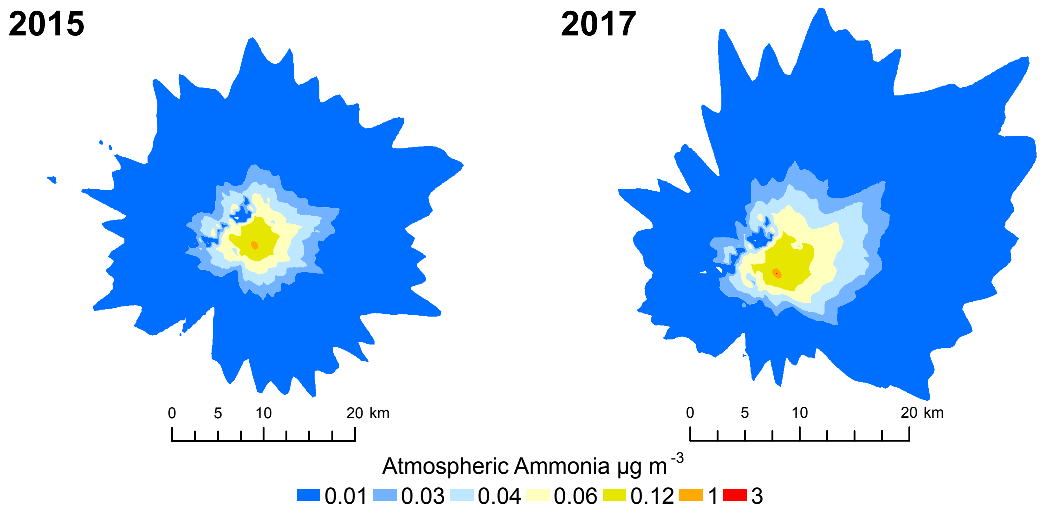

Figure 3.4. Modelled dispersion of ammonia from monitored Pig Farm 1 in 2015 and 2017.

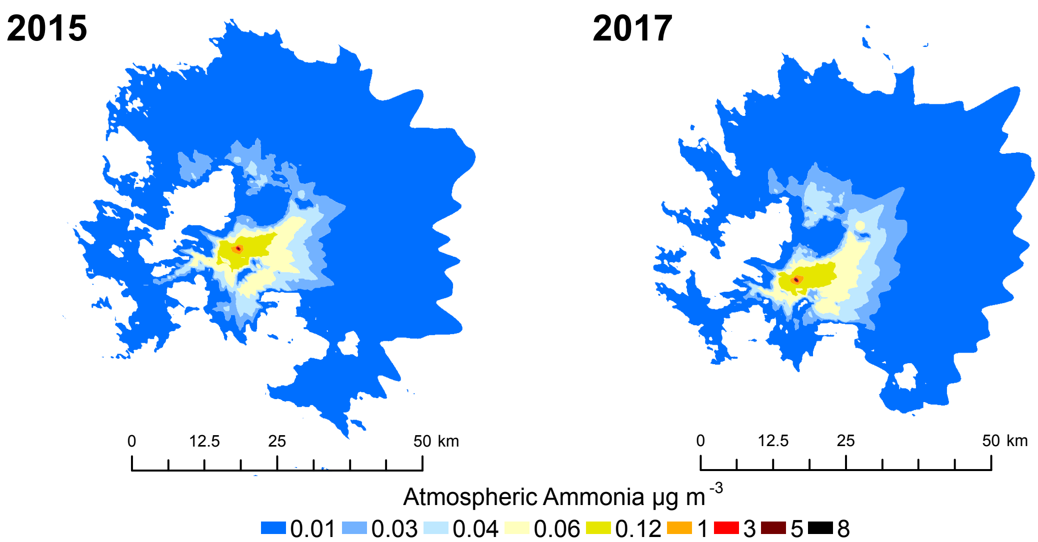

Figure 3.5. Modelled dispersion of ammonia from monitored Pig Farm 2 in 2015 and 2017.

Exceedance of 1 µg NH_3 m^{-3} is also representative of exceeding the empirical critical load of 5 kg N ha^{-1} year^{-1}. Similarly, 3 µg NH_3 m^{-3} is exceeded within 187 m of the Broiler Farm, within 172 m of the Layer Farm, within 389 m of Pig Farm 1 and within 1685 m of Pig Farm 2. This represents the exceedance of both the higher limit for species change points identified by Wilkins (2016a) for other habitats and the highest empirical critical load of 20 kg N ha^{-1} year^{-1} for woodlands. The influence of ventilation rate on both the emission rate and exit velocity is vitally important when considering potential impacts from pig and poultry houses, influencing both the dispersion extent and the plume concentration. When considering potential impacts on Natura 2000 sites as designated by the Habitats Directive, cognisance should be given to precautionary principle and, unless detailed site-specific emission rates are available, the highest potential rates should be applied. This work highlights that both the highest and lowest possible ventilation rates should be considered under the precautionary principle, as both can underestimate either the extent or concentration of the dispersion plume. The maximum extents of these models are not necessarily realistic, because of the lack of chemical conversion and depletion. Regardless, modelling to the extent of 0.01 µg NH_3 m^{-3} is important, because, if and when this concentration is exceeded in UK regulatory bodies, detailed dispersion modelling is required.

3.3 Exceedance of De Minimis Deposition Values

The EU Network for the Implementation and Enforcement of Environmental Law (IMPEL) has published guidance setting 0.3 kg N ha^{-1} year^{-1} as a de minimis value for project contributions (IMPEL, 2017). As such, the point at which contributions from each monitored farm exceeded 0.3 kg N ha^{-1} year^{-1} for both woodlands and other habitats were mapped and graphed in Figure 3.6. Deposition is much higher on woodland habitats because of the higher deposition velocity of 0.03 m s^{-1}; as a result, a lower concentration of ammonia yields 0.3 kg N ha^{-1} year^{-1} at

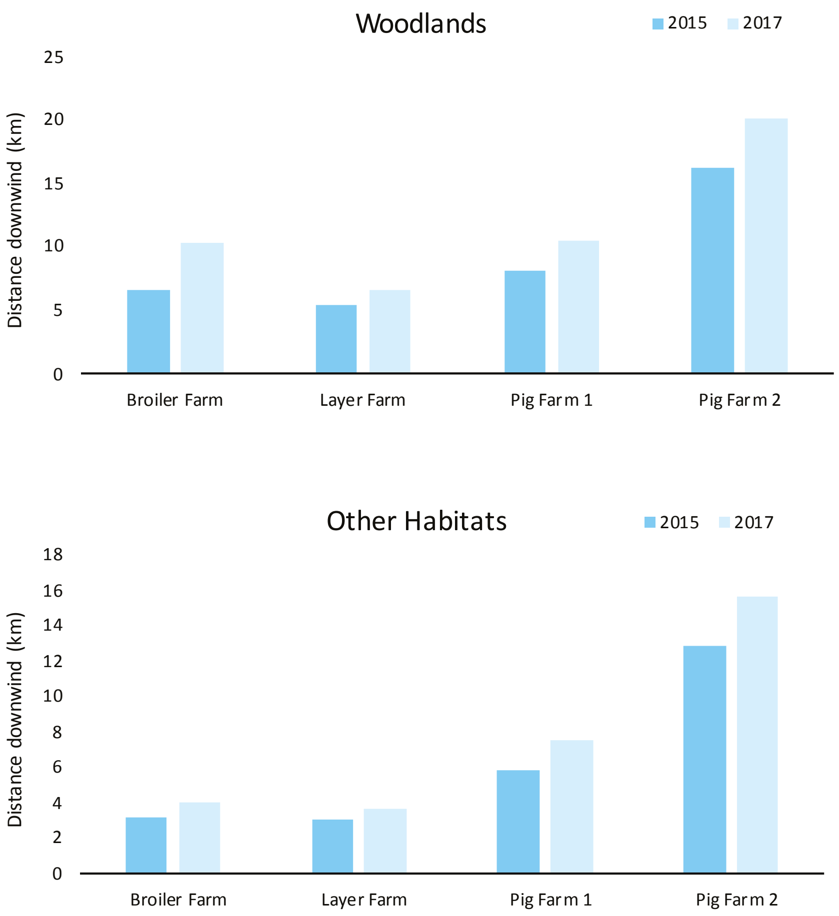

Figure 3.6. Maximum distance downwind from farms where dry deposition of ammonia exceeds 0.3 kg N ha^{-1} year^{-1}.

a greater distance from the farm compared with other habitats (deposition velocity of 0.02 m s^{-1}). Comparing deposition on woodlands with that on other habitats suggests that this deposition rate from monitored farms can be reached within 5–20 km of woodlands and within 3–15 km of other habitats (Figure 3.6). The maximum extent for this rate to be exceeded for every farm occurs in 2017, when meteorological conditions resulted in the greatest dispersion extent of years between 2013 and 2017. Dispersion modelling from monitored farms indicates that 0.3 kg N ha^{-1} $year^{-1}$ was exceeded for the Broiler Farm, Layer Farm, Pig Farm 1 and Pig Farm 2 within 3–10 km, 3–7 km, 6–10 km and 13–20 km, respectively. These distances are dependent on both the year and deposition velocity. This indicates that the use of a 10-km buffer for all farms is appropriate to screen de minimis values, with the exception of the larger Pig Farm 2. Caution should be applied with such large farms; if using a distance screening threshold to rule out contribution to negative ecological effects, a 20-km buffer may be appropriate.

4 Intensive Agriculture Installations

The intensive rearing of poultry and pigs is an industry that may currently require licensing under the IED (2010/75/EU). The EPA is responsible for IED (previously Integrated Pollution Prevention and Control – IPPC) licensing in Ireland, whereby it seeks, among other objectives, to reduce emissions from facilities that are licensed. Under EU legislation, only poultry farms where capacity exceeds 40,000 birds and pig farms where capacity exceeds 750 sows or more than 2000 finisher pigs require licensing under this directive. Any farm that exceeds these criteria must hold an IED licence issued by the EPA and the farm is thereby subject to stricter controls than an unlicensed, smaller farm. The EPA has not previously had access to the locations of unlicensed or sub-threshold farms and therefore their contributions to cumulative impacts could not previously be assessed. Below-threshold farms are not required to comply with BAT guidance and without reduction requirements they could potentially contribute to greater cumulative impacts than licensed facilities (Aazem and Bareham, 2015). Although pig and poultry farms contribute a small portion of total national emissions (7%), areas proximal to these units have been shown to have the highest concentrations of ammonia (Tang *et al*., 2018) and therefore where they occur they have a higher potential to contribute to local ecological impacts.

4.1 Identifying Below-IED Threshold Farms

The AmmoniaN2K project conducted a comprehensive review of local authority planning applications and satellite imagery to identify the majority of unlicensed/below-threshold facilities in Ireland for 2015. It was not possible to determine the type of poultry (broiler, layer, duck, goose, turkey, breeder, etc.) or pig (finisher, sow, weaners, etc.) house identified or if the farms were currently in operation. Regardless, they are potential hotspot sources of atmospheric ammonia. An additional 560 poultry and 200 below-threshold pig facilities were identified using this approach. As of spring 2019, there were 110 poultry units and 120 pig units licensed by the EPA, resulting in potential totals of 670 poultry and 320 pig farms.

The number and locations of unlicensed houses identified are by no means comprehensive; it is possible that not all facilities have been identified and that some of the identified facilities may not be currently operational. It can, however, be considered representative of unlicensed facilities and a baseline that can be built upon in the future. It is important not to exclude unlicensed facilities from future assessments, in particular as research in Northern Ireland has shown impacts from atmospheric ammonia downwind of such facilities (A.J. Dore, UK Centre for Ecology & Hydrology, 15 March 2018, personal communication). Any cumulative assessments carried out will need to take cognisance of both above- and below-threshold pig and poultry farms, in addition to other sources, such as cattle and land spreading of slurry. Contributions from cattle and slurry spreading have traditionally been considered diffuse sources of ammonia because of the vast extent that they cover. However, a recent ruling by the European Court of Justice has determined that both grazing and slurry spreading constitute projects that need to be assessed for impacts on Natura 2000 sites under the Habitats Directive (EU, 2019). This sets the precedence that both processes, which were previously presumed to not impact significantly on habitats, do in fact contribute to cumulative impacts on Natura 2000 sites. The contributions of pig and poultry farms in combination with other sources of ammonia will be discussed further in Chapter 5 of this report.

Figure 4.1 shows the locations of both licensed and unlicensed pig and poultry farms in Ireland within a 10-km grid. The highest number of licensed pig farms within 10 km is in County Cavan, with five licensed facilities. Six to eight farms was the highest number of unlicensed facilities in a 10 km grid; these were in County Cavan and there was also one grid in south County Tipperary. County Monaghan has by far the highest density of licensed and unlicensed poultry facilities in Ireland, with 11–16 licensed and 36–50 unlicensed facilities occurring within a 10-km grid. West County Limerick and east County Cavan are also apparent hotspots for poultry farms. The density of poultry farms is probably linked to proximity to processors.

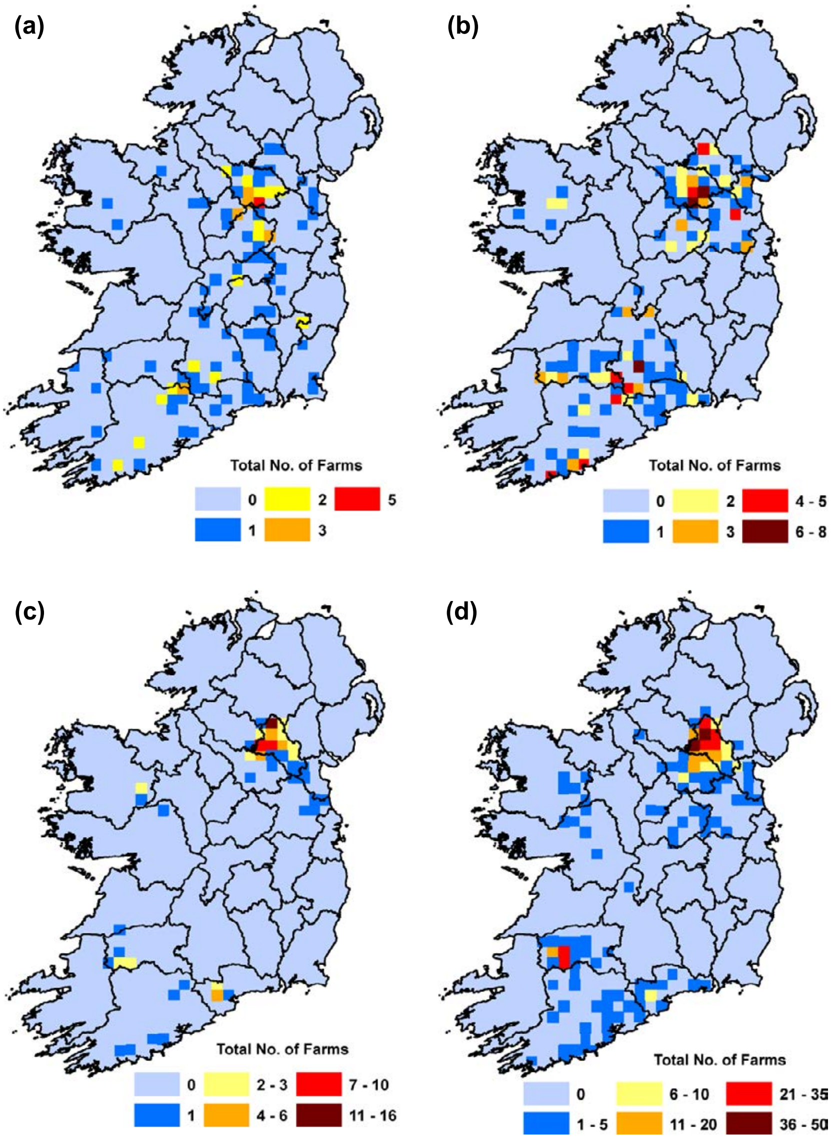

Figure 4.1. (a) IED-licensed pig farms. (b) Below-IED threshold pig farms. (c) IED-licensed poultry farms. (d) Below-IED threshold poultry farms.

4.2 Potential Cumulative Impacts from Pig and Poultry on Natura 2000 Sites

The use of distance screening thresholds is often the first step in stage 1 AA under the Habitats Directive. Modelling the overlapping distance thresholds from licensed and unlicensed pig and poultry farms is a useful indicator of areas at risk from these sites. The Scottish Environment Protection Agency recommends the use of a 10 km screening distance for ammonia impacts on Natura 2000 sites, which is the most precautionary in the UK (Scottish Environment Protection Agency, 2018). However, the UK Environment Agency recommends the use of a 5-km screening threshold (Environment Agency, 2018).

The distance threshold selected for this study was 10 km, as the most precautionary recommended by UK agencies. The use of screening distance thresholds is a valuable first step to identifying areas potentially at risk. ArcGIS was used to create a 10-km buffer around every Natura 2000 site in Ireland; this was used to summarise the number of licensed and unlicensed intensive agriculture units within 10 km of every Natura 2000 site. The number of licensed and unlicensed pig and poultry farms within 10 km of every Natura 2000 site is provided in Appendix 3. As the below-threshold intensive agriculture units have previously gone unidentified, this is the first time that these farms are considered to be contributing to cumulative impacts on Natura 2000 sites from atmospheric ammonia.

Figure 4.2a–c shows the number of overlapping 10-km buffers for pigs and 10-km buffers for poultry farms. This is inclusive of both licensed and unlicensed farms. This shows that there are areas in which ammonia emissions from up to nine pig units, and as many as 200 poultry units, may be having an impact on a site.

Figure 4.2c sums the pig and poultry buffers as an indicator of total cumulative impact from pig and poultry farms combined. This is presented on a range of 0–202 overlapping buffers from intensive agriculture units. This is further summarised per Natura 2000 site in Figure 4.2d, which shows the number of overlapping buffers within each Natura 2000 site in Ireland. There are Natura 2000 sites that are within the range of ammonia emissions from 120 pig and poultry farms. Further detailed dispersion modelling and monitoring is required in order to ascertain the actual impacts on these sites, as the use of buffers in this case is a worst-case scenario. In reality, prevailing wind conditions may reduce the risk of cumulative impacts on these sites. Additionally, results from Chapters 2 and 3 highlight that, although emissions from monitored poultry houses spread further, they contributed much less to the concentration of ammonia than pig farms.

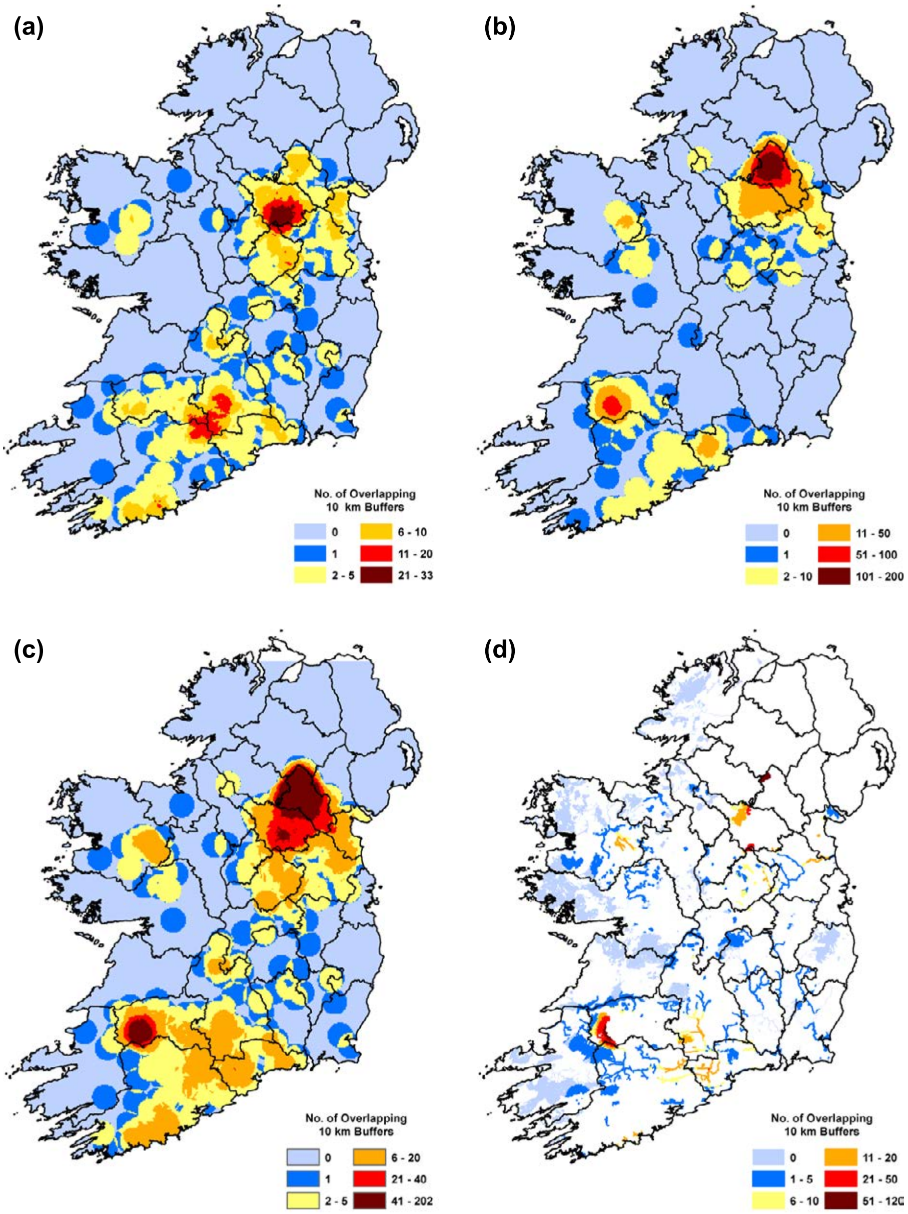

Figure 4.2. Overlapping 10 km buffers from all licensed and unlicensed (a) pig, (b) poultry and (c) both combined. (d) The number of overlapping 10 km pig and poultry farm buffers within the Natura 2000 network of designated sites.

5 Cumulative Risk to Natura 2000 Sites

In the UK, a detailed atmospheric ammonia concentration and deposition model (FRAME) is used to estimate the impact of atmospheric ammonia on the UK Natura 2000 network of designated sites. FRAME dispersion modelling utilises the national spatial emissions model (e.g. Hellsten *et al*., 2008), which incorporates all sources of atmospheric ammonia. This model estimates surface air concentrations of ammonia at 5 and 1 km resolution, allowing for exceedances of critical levels to be easily identified (Hallsworth *et al*., 2010). Hallsworth *et al*. (2010) used two approaches to summarise the extent of impacts across the Natura 2000 network of designated sites, namely Area Weighted Indicator (AWI) and Designation Weighted Indicator (DWI). The DWI estimated the number of Natura 2000 sites that exceed a critical level in any area of the site; this approach was considered more relevant by the authors under the terms of the Habitats Directive. The AWI included an estimation of the total coverage of Natura 2000 sites exposed to the different critical levels. Using the AWI, it was estimated that 11.2%, 1.3% and 0.2% of the area of the UK Natura network exceeds the critical level values of 1, 2 and 3 $\mu g\, NH_3\, m^{-3}$, respectively. By contrast, using the DWI, the equivalent exceedances were 59.1%, 23.6% and 9.8%. Exceedance over part of a Natura site was considered to represent a threat to the integrity of the whole site (Hallsworth *et al*., 2010). As impacts from atmospheric ammonia arising from intensive pig and poultry production occur in combination with all other sources of ammonia, this chapter details a cumulative assessment of potential impacts on Natura 2000 sites from all reported sources of ammonia. The extensive production system for cattle in Ireland, inclusive of land spreading, is the primary contributor to ambient concentrations of ammonia (Doyle *et al*., 2017); it exceeds the critical level for lichens and moss species across most of the country. Contributing additional ammonia from intensive point sources, such as pig and poultry farms, will potentially exacerbate any ammonia impacts already potentially occurring on site.

5.1 Atmospheric Ammonia Risk Modelling

As all past national ammonia monitoring programmes in Ireland (Doyle *et al*., 2017; de Kluizenaar and Farrell, 2000) have been designed to intentionally exclude areas in which intensive agricultural installations occur, the data generated by these studies are not alone suitable to gauge the national risk to Natura 2000 sites from atmospheric ammonia. The AmmoniaN2K adapted a geographic information system (GIS) risk-based approach in order to identify areas most at risk from agricultural atmospheric ammonia, using best available data. The model produced, entitled “Mapping Ammonia Risk on Sensitive Habitats” (MARSH), was published in 2019; section 5.2 is based on this publication (Kelleghan *et al*., 2019). This approach considers contributions of ammonia from other sources in addition to intensive pig and poultry farms. MARSH modelling does not consider contribution of other nitrogenous pollution (e.g. nitrogen dioxides from motor vehicles), but instead focuses on the risk posed to habitats and species from agricultural ammonia.

This approach identified potential agricultural sources of atmospheric ammonia, creating an indicative heat map for each source on a scale of 0–5, where 5 is representative of the area with the highest risk (i.e. highest cattle/sheep numbers, highest density of intensive agriculture, areas most likely to receive synthetic fertiliser, etc.). The risk maps were subsequently summed based on a weighting determined by each source’s contribution to national emissions, divided by the area that it occupies. An indicative risk map on a scale of 0–5 of areas most likely to be affected by atmospheric ammonia was created. FRAME modelling for Northern Ireland was used to assign concentration values to the MARSH model for both Northern Ireland and Ireland (Kelleghan *et al*., 2019). The monitoring conducted by Doyle *et al*. (2017) was then used to validate this model, comparing modelled and monitored concentrations, and was subsequently used to correct the concentration map. The final MARSH map is a risk map based on likely concentrations of ammonia present in these locations inclusive of all potential sources (excluding below-IED threshold houses, which have not been validated) (Figure 5.1a). Ecological indicators of nitrogen pollution are often used during surveys to infer impacts of atmospheric ammonia (Frati *et al.*, 2006; Cape *et al.*, 2009; Rihm *et al.*, 2009); lichens are particularly useful, because, as they do not have a root system, lichens rely on sourcing nutrients from the atmosphere. Lichen records provided by the Centre for Environmental Data and Recording (CEDaR) were used as an indicator of affected and unaffected areas based on the tolerance of species present, following the approach of Rihm *et al.* (2009). In Figure 5.1b affected areas are represented by a value of +1 and unaffected areas by a value of –1.

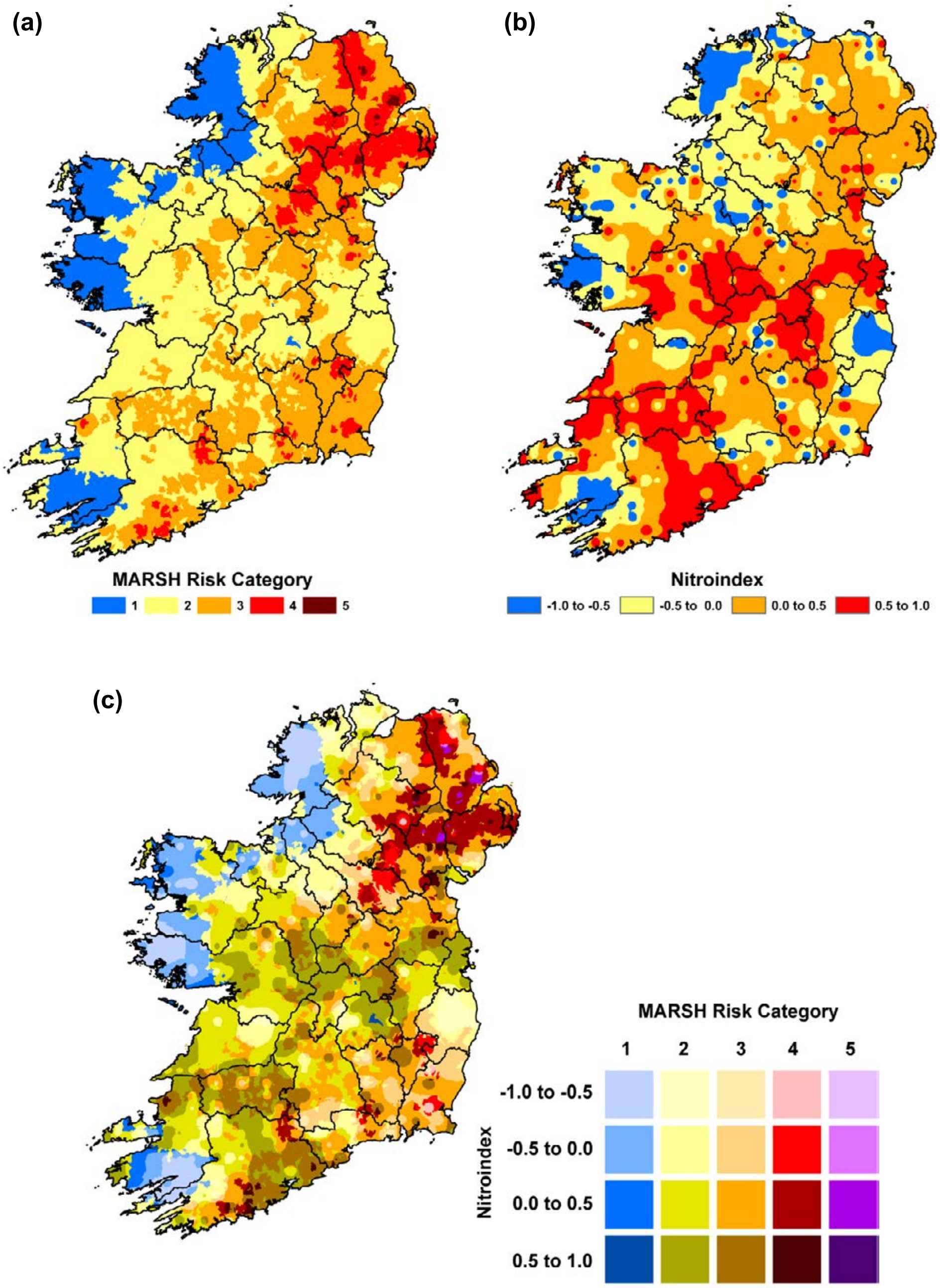

Figure 5.1. (a) Final MARSH model, where MARSH risk categories 1, 2, 3, 4 and 5 correspond to probable atmospheric ammonia concentrations of 0–1, 1–2, 2–3, 3–4 and >4 µg NH_3 m^{-3}, respectively. (b) Nitroindex values range from –1 (unaffected) to +1 (affected) based on nitrogen-sensitive lichen species. (c) Bivariate map showing both the final MARSH model and the Nitroindex. Adapted from Kelleghan *et al.* (2019). The URL from which the shapefiles can be downloaded is available in Appendix 5.

This was integrated into the MARSH model to create a bivariate map of impacts (Figure 5.1c).

When considering impacts on Natura 2000 sites, it is important to understand the sensitivity of each site. An extensive review of all Natura 2000 sites in Ireland was conducted by the AmmoniaN2K project, in which a critical level was assigned to every conservation feature of every site (see Appendix 4). For SACs this was based primarily on whether or not a conservation feature had a strong association with lichens or moss species, in which case they were assigned a critical level of 1 µg NH_3 m^{-3}; otherwise they were given a critical level of 3 µg NH_3 m^{-3}. If a SAC has a conservation feature with a critical level of 1 µg NH_3 m^{-3}, this critical level was applied to the whole site; this approach was precautionary, highlighting primarily the potential for impacts. Otherwise it was assigned a critical level of 3 µg NH_3 m^{-3}, which is the critical level used for higher plants. SPAs designated for the conservation of bird species were included in analysis, as, although there are no direct impacts on birds from atmospheric ammonia (based on current knowledge), they can experience indirect impacts through changes in their habitat. The proportion of habitats within SPAs with a potential critical level of 1 µg NH_3 m^{-3} (i.e. bogs, heath and broadleaf woodland) based on CORINE (Coordination of Information on the Environment) habitat mapping was used to indicate potential risk to these sites. The sensitivity of SACs and SPAs for each site is provided in Appendix 3 and a summary of the risk to sites across the island of Ireland can be found in Table 5.1. Table 5.1 shows the percentage of each sensitivity class of Natura 2000 site and the potential risk based on MARSH-modelled concentrations. Where an SAC has a critical level of 1 µg NH_3 m^{-3}, any concentration above 1 µg NH_3 m^{-3} may have negative effects on a site. Similarly, at sites with a critical level of 3 µg NH_3 m^{-3}, concentrations exceeding 3 µg NH_3 m^{-3} may negatively affect biodiversity within the site. SPAs are separated based on the proportion of potentially sensitive habitat within each SPA based on CORINE habitat mapping. Percentages represent the proportion of SPAs exposed to varying concentrations.

Table 5.1 is further summarised in Table 5.2, which presents the total number of SACs that exceed concentrations of atmospheric ammonia based on designated weighted indicators, which are more representative of potential impacts on Natura 2000 sites (Hallsworth *et al*., 2010). In Table 5.2 it can be seen that 389 SACs and 142 SPAs exceed a concentration of 1 µg NH_3 m^{-3}, 161 SACs and 65 SPAs exceed a concentration of 2 µg NH_3 m^{-3}, and 25 SACs and 14 SPAs exceed a concentration of 3 µg NH_3 m^{-3}. A detailed breakdown of the proportion of every Natura 2000 site within each risk category and the site's sensitivity is presented in Appendix 3.

The availability of data limited the creation of the MARSH model, where the locations of below-threshold pig and poultry houses were not available during its creation. Additionally, the most recent data available for cattle and sheep populations are from 2010 (CSO, 2010) and no data are available for slurry spreading. As such assumptions needed to be made, where, for example, it was presumed that areas with high animal production would be less likely to use synthetic

Table 5.1. The percentage of Natura 2000 sites that at some locations fall within MARSH risk categories

	MARSH risk category				
Proxy ammonia concentration	**1**	**2**	**3**	**4**	**5**
SAC CL of 1 µg NH_3 m^{-3}	30.7	66	33.7	5.5	0.3
SAC CL of 3 µg NH_3 m^{-3}	22.9	66	28.8	4.6	0
SPA 1–10% CL of 1 µg NH_3 m^{-3}	24.2	69.5	39.8	8.6	0
SPA 11–50% CL of 1 µg NH_3 m^{-3}	35.7	78.6	35.7	3.6	0
SPA 51–100% CL of 1 µg NH_3 m^{-3}	50	60	20	10	0
All SACs	28.2	66	32.2	5.2	0.2
All SPAs	29	69.9	36.9	8	0
All Natura 2000 sites	28.4	67	33.4	5.9	0.2

Notes: a site can be exposed to multiple concentrations; MARSH risk categories 1, 2, 3, 4 and 5 correspond to likely atmospheric ammonia concentrations of <1, 1–2, 2–3, 3–4 and > 4 µg NH_3 m^{-3}, respectively.

CL, critical level.

Presented from Kelleghan *et al.* (2019).

Table 5.2. Proportion of Natura 2000 sites that exceed proxy atmospheric concentration values based on DWIs

Critical level	Total no.	> 1 µg NH_3 m^{-3}	> 2 µg NH_3 m^{-3}	> 3 µg NH_3 m^{-3}
SAC count	482	389	161	25
SPA count	176	142	65	14
All Natura 2000 count	658	531	226	39
All Natura 2000 (%)	–	80.7	34.3	5.9

Note: a site can be exposed to multiple concentrations.
From Kelleghan *et al.* (2019).

fertiliser and areas with high animal production would spread manure locally. This presumption, where the opposite is also likely accounted for 7% of the MARSH model and is further corrected for by integrating the monitored concentrations on 25 sites (Doyle *et al.*, 2017) and linking recorded ecological impacts in the form of lichen records. Based on modelling in earlier chapters, it is anticipated that concentrations near hotspot sources could be substantially higher than MARSH predictions. Further modelling may be required to quantify the risk posed by these sites, particularly in relation to cumulative impact assessment, as required under the Habitats Directive.

5.2 Monitoring Atmospheric Ammonia on Natura 2000 Sites

The MARSH modelling estimates the atmospheric concentration across the entire Natura 2000 network in Ireland; however, it is important to also conduct monitoring in order to validate any model assumptions. Atmospheric ammonia was monitored on 12 Natura 2000 sites in Ireland in co-operation with the National Parks and Wildlife Service (NPWS) and the Living Bog Life project. This monitoring used three ALPHA samplers at 1.5 m high on every Natura 2000 site presented in Table 5.3. ALPHA samplers are passive ammonia samplers that measure atmospheric ammonia concentrations. They were provided to this project by the UK Centre for Ecology & Hydrology. A filter paper coated in citric acid absorbs atmospheric ammonia, allowing for analysis using spectrophotometry to identify how much was absorbed. Samples were exposed for approximately 30-day periods. A sample was co-located with a DELTA sampler in Lough Navar, Northern Ireland, as cross-calibration with this form of atmospheric ammonia is required to calibrate lower accuracy passive samplers.

Results of monitoring carried out on Natura 2000 sites are presented in Table 5.3. The MARSH model was generated using the best available data at the time, whereas monitored concentrations are representative of the year that monitoring was conducted. The most recent data available for cattle and sheep populations are from the 2010 agricultural census (CSO, 2010). With significant increases in dairy herds since 2010, incorporating these data is what inspired the use of a relative risk approach rather than modelling directly from animal numbers. Additionally, when this model was generated, the below-IED threshold pig and poultry farms had not yet been identified and so this information will improve future models. Slurry spreading is also poorly predicted by the MARSH model, for which data are not available. Local slurry spreading practices can also alter the concentration on site, where, for example, the monitored concentration of 4.52 µg NH_3 m^{-3} on Lough Lene is a direct result of regular slurry spreading observed by the conservation ranger on site.

The monitoring of ammonia concentrations on Natura 2000 sites validates the use of the MARSH model as a scale of relative risk, with a Pearson correlation coefficient of 0.7 across all sites (Figure 5.2a). However, the MARSH model predominantly underestimates concentrations on sites. Table 5.3 shows concentrations underestimated on 10 of the 12 sites, at a range of 0.2–2.17 µg NH_3 m^{-3}. It also overpredicts concentrations on two sites, at a range of 0.45–0.65 µg NH_3 m^{-3}. It is expected that the Bricklieve Mountains are overpredicted, as the MARSH model did not consider the reduction of ammonia at a high elevation. The increased concentration on Brown Bog SAC may be the result of changes in agricultural practices since the collection of data used to generate the MARSH model. When both these sites

Table 5.3. Modelled MARSH and monitored atmospheric ammonia (NH_3) concentrations on 12 Natura 2000 sites in Ireland

Site name	County	Most sensitive qualifying interest	Critical level (µg NH_3 m^{-3})	MARSH modelled concentration (µg NH_3 m^{-3})	Monitored annual average concentration (µg NH_3 m^{-3})
Wicklow Mountains SAC	Wicklow	Blanket bogs (active)[a] [7130]	1	0.4	0.57
Blackwater River (Cork/ Waterford) SAC	Cork	*Margaritifera margaritifera* (freshwater pearl mussel) [1029]	1	1.19	2.7
Killyconny Bog (Cloghbally) SAC	Cavan	Active raised bogs[a] [7110]	1	1.96	2.3
Wexford Harbour and Slobs SPA	Wexford	Wetland and waterbirds [A999]	3	3.09	3.11
Raheenmore Bog SAC	Offaly	Active raised bogs[a] [7110]	1	1.72	2.34
Spahill and Clomantagh Hill SAC	Kilkenny	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*) (* important orchid sites) [6210]	1	1.95	2.29
Bricklieve Mountains and Keishcorran SAC	Sligo	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*) (* important orchid sites) [6210]	1	1.12	0.47
Ardagullion Bog SAC	Roscommon	Active raised bogs[a] [7110]	1	1.44	2.92
Brown Bog SAC	Longford	Active raised bogs[a] [7110]	1	3.12	2.24
Garriskil Bog SAC	Westmeath	Active raised bogs[a] [7110]	1	0.78	1.18
Lough Lene SAC	Westmeath	*Austropotamobius pallipes* (white-clawed crayfish) [1092]	3	2.41	4.59
Scragh Bog SAC	Westmeath	Transition mires and quaking bogs [7140]	1	0.95	1.4

[a]Annex I priority habitat.

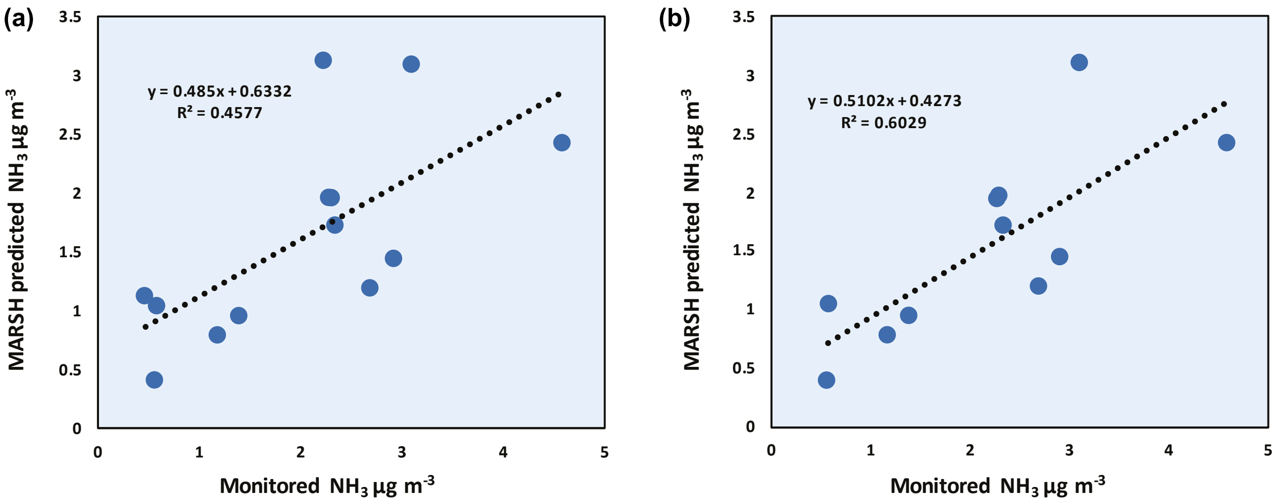

Figure 5.2. Scatterplots of predicted ammonia concentrations by the MARSH model and monitored concentrations on site by ALPHA samplers. (a) All sites, with a Pearson correlation coefficient of 0.7. (b) Excluding Brown Bog, Bricklieve Mountains and Keishcorran SACs, with a Pearson correlation coefficient of 0.8.

are removed from analysis, the Pearson correlation coefficient increases to 0.8 (Figure 5.2b).

Both the results of the monitoring and the comparison with predicted concentrations show that the MARSH model effectively estimates risk to Natura 2000 sites, though generally it underpredicts concentrations. It also identifies the seriousness of the threat from ammonia concentrations in Ireland, confirming the need for further modelling and monitoring of ammonia concentrations in Ireland.

5.3 Ecological Effects from Other Sources

A field survey was conducted in February 2019 on Raheenmore Bog SAC in order to identify potential ecological effects of ammonia on site. Raheenmore Bog SAC is not downwind of any intensive point sources of ammonia, the nearest of which are two IED-licensed pig farms, one 2.5 and one 5 km upwind of the site. Because of the distance and wind direction, these are not likely to contribute significantly to local concentrations of ammonia on site; however, additional modelling may be required to clarify this. The more likely source of ammonia on this site is from nearby cattle farms and slurry spreading in neighbouring pasture, which is the most frequently occurring habitat. The provisional concentration monitored on this site exceeded the lower critical level of 1 μg NH_3 m^{-3} at 2.3 μg NH_3 m^{-3}; section 5.2 has identified that 35% of Natura 2000 sites are likely to also exceed this concentration. Additional ecological surveys are required not only on monitored Natura 2000 sites in this study but also across the entire network of designated sites.

A quick walkover revealed evidence of the site receiving at least an intermediate level of impact from atmospheric ammonia (M. Sutton, UK Centre for Ecology and Hydrology, 4 February 2019, personal communication). Ecological indicators of ammonia pollution are presented in Figure 5.3a–f. Damage to reindeer lichen (*C. portentosa*) – shown in Figure 5.3a – has been recorded in response to increased levels of ammonia and exposure to direct sunlight (Sheppard *et al*., 2011), where the normally bluish green lichen is tinged with pink. Additionally, Figure 5.3 shows a patch of decaying peat moss (*Sphagnum* sp.), which is often reported as an impact from atmospheric ammonia and nitrogen pollution (Sheppard *et al*., 2011; Sutton *et al*., 2011). Increased algal biomass has also been reported as a result of ammonia exposure on peatlands (Payne *et al*., 2013). Figure 5.3b–f shows the abundance of algae on Raheenmore Bog, whereas Figure 5.3b–d

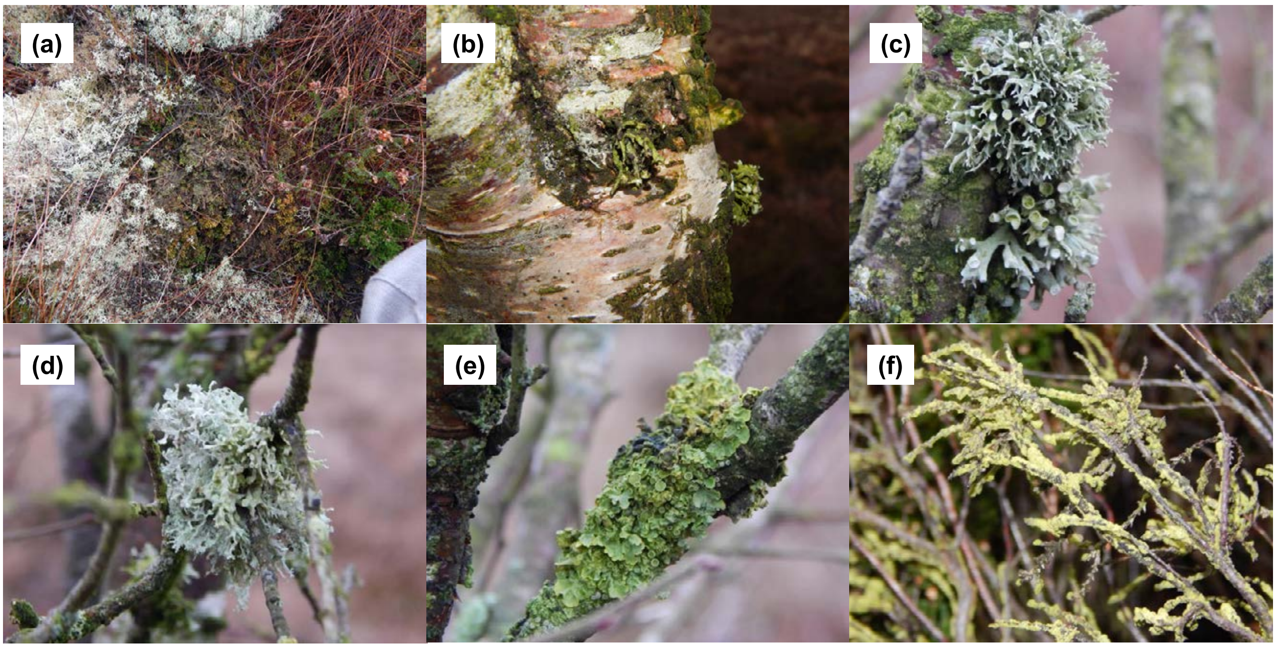

Figure 5.3. (a) Evidence of decaying *Sphagnum* and off-colour *C. portentosa*. (b–d) Nitrogen-sensitive lichen species being encroached by green algae. (e) *Xanthoria* species as an indicator of ammonia pollution. (f) Dead heather colonised by green algae.

shows it encroaching on epiphytic lichens. It was also extensively observed on patches of dead heather across the bog (see Figure 5.3f). Other indicators of ammonia pollution included the presence of nitrogen-tolerant epiphytic lichen species, such as the scaly lichen yellow scale (*Xanthoria* sp.) shown in Figure 5.3e (UK Centre for Ecology & Hydrology, 2015).

6 Conclusions and Recommendations

In summary, the need to research and quantify the impact of ammonia emissions from intensive pig and poultry units on Natura 2000 sites in Ireland has resulted in a number of valuable conclusions and recommendations. These are intended to assist the EPA licensing of intensive agriculture installations, in particular to support AAs under the Habitats Directive, contribute to national inventory reporting and PRTR reporting, assist in the assessment of developments under Food Harvest 2020 and Food Wise 2025 and support work under the CLRTAP. Conclusions and recommendations are subdivided into the following categories: emission rates, emission reductions, ecological impacts, policy and future work.

6.1 Emission Rates

- When considering potential impacts on Natura 2000 sites, the precautionary principle should be applied and the maximum potential emission rate should be used, unless site-specific information is available.
- The broiler emission rate presented in the EPA's AER/PRTR guidance was originally calculated by presuming a bird weight of 2 kg, which in Irish production systems is generally the bird's finishing weight rather than its average weight. Although the modelled emission rate supports the use of the higher rate used by the EPA, further monitoring is required over a wider network of farms to validate this. The monitored farm was in an area with a high density of other hotspot sources of ammonia, which could potentially artificially increase the monitored emissions. This figure could be recalculated to represent the bird's average weight during its production cycle. The rate presented in the EPA's AER/PRTR guidance is in g NH_3 bird^{-1} day^{-1}. Dispersion modelling to assess the exceedance of annual critical levels and loads requires consideration of non-production days, i.e. the total emissions should be averaged over 365 days, rather than 231 days as recommended in AER/PRTR guidance.
- Broiler emission rates monitored were 0.04 kg NH_3 bird^{-1} year^{-1}, which reached 0.06 kg NH_3 bird^{-1} year^{-1} when modelled to include two full 37-day cycles. These annual rates were calculated presuming 231 production days outlined as the average cycle length in Ireland by the EPA. The SCAIL-Agriculture emission rate of 0.03 kg NH_3 bird^{-1} year^{-1} is calculated using 278 production days, highlighting the importance of production days and cycle lengths in emission rates for broilers. Cycles with fewer days have lower emissions and years with fewer production days also produce lower emissions. A study to optimise animal growth, market demand and reduced emission rates would benefit the poultry sector and the environment, as changes in practice may reduce emissions while also benefiting the farmer.
- Layer monitoring of caged birds provided an emission rate of 0.09 kg NH_3 bird^{-1} year^{-1}, which is lower than the EPA's currently used figure of 0.15 kg NH_3 bird^{-1} year^{-1}; however, this is an average of both caged and deep pit birds. When the rate is recalculated to include just caged birds, a similar rate of 0.08 kg NH_3 bird^{-1} year^{-1} is obtained. In this case, the SCAIL-Agriculture emission factor for whisk-forced air drying (0.09 kg NH_3 bird^{-1} year^{-1}) is more representative than standard forced drying (0.12 kg NH_3 bird^{-1} year^{-1}). The SCAIL-Agriculture figure is appropriately precautionary to predict impacts from dispersion into the atmosphere, with the difference in both rates highlighting the value of different approaches to manure drying.
- Emission rates monitored for dry/pregnant sows are higher in all three houses monitored than the values used either by the EPA (3.17 kg NH_3 animal^{-1} year^{-1}) or SCAIL-Agriculture (3.01 kg NH_3 animal^{-1} year^{-1}). The housing on Pig Farm 2, with a range of 4.46–4.94 kg NH_3 animal^{-1} year^{-1}, is similar to the value for traditional housing in the Netherlands (4.2 kg NH_3 animal^{-1} year^{-1}) and monitoring by Hayes *et al.* (2006a) (3.87–4.93 kg NH_3 animal^{-1} year^{-1}). The value of 5.58 kg NH_3 animal^{-1} year^{-1} on Pig Farm 1 is probably higher as a result of the increased

ventilation rate of mechanical ventilation, compared with the two naturally ventilated houses on Pig Farm 2. This highlights the influence of ventilation type on emissions, with houses that utilise only mechanical ventilation having higher emission rates. The monitoring of both this and past projects shows that both SCAIL-Agriculture and EPA emission rates can underestimate potential emissions from dry/pregnant sow housing.

- The emission rates observed within farrowing houses broadly support the use of the SCAIL-Agriculture emission factor of 5.84 kg NH_3 animal^{-1} year^{-1}, though those observed by this study (6.57–6.61 kg NH_3 animal^{-1} year^{-1}) and Hayes *et al*. (2006a) (5.95–6.50 kg NH_3 animal^{-1}year^{-1}) were slightly higher. The EPA currently recommends the use of an emission factor of 4.72 kg NH_3 animal^{-1} year^{-1} for AER/PRTR reporting, which is much lower than other monitored emission rates listed in this report.
- The EPA AER/PRTR guidance combines stage 1 and stage 2 weaners at one emission factor of 0.99 kg NH_3 animal^{-1} year^{-1}, which is slightly higher than the average of stage 1 weaners and grower pigs over slatted floors as classified by SCAIL-Agriculture, at 0.94 kg NH_3 animal^{-1} year^{-1}. The average of stage 1 and stage 2 weaners for both the AmmoniaN2K project and Hayes *et al*. (2006a) was in the range of 0.69–1.14 kg NH_3 animal^{-1} year^{-1}. SCAIL-Agriculture can be used to provide detailed emission rates for both stage 1 and stage 2 (growers in SCAIL-Agriculture report). This monitoring highlighted the importance of weight classification for different weaner stages, with Farm 1 probably having lower emissions on account of the inclusion of three stages rather than two. This also highlights the benefit of splitting weaner stages into separate categories, as has been done in the SCAIL-Agriculture report, as different housing systems for different stages have different emission rates and generating an average for all weaner types could be giving a false impression of BAT compliance.
- Finishing pig ammonia emissions seem to vary significantly depending on the house that they are raised in. This project observed a range of 2.00–3.99 kg NH_3 animal^{-1} year^{-1}, with this diversity observed on a single farm from animals on the same diet in different houses. This is similar to the range of data originally used by the EPA at 1.72–3.54 kg NH_3 animal^{-1} year^{-1} to produce an averaged emission factor of 2.64 kg NH_3 animal^{-1} year^{-1}. With such a diversity of emission rates, the precautionary principle should be applied when modelling impacts from atmospheric ammonia, in which case the SCAIL-Agriculture emission factor of 4.14 kg NH_3 animal^{-1} year^{-1} should be used, unless detailed information for the site being modelled is available.
- The only finishing house monitored by this project to exceed the upper BAT-AEL was the most modern house. Higher ventilation and emission rates from the modern ventilation system removed ammonia from within the building quicker. This house was noted to be the cleanest inside with noticeably less pungent air, which would leave anyone visiting this house to presume it was the most environmentally friendly; in fact, it had the highest finisher emission rates observed in this project. Hence, caution should be applied to presumptions made about new housing as a clean interior with noticeably cleaner air without emission reduction strategies in place is potentially an indicator of high emission rates.
- The ventilation rate of houses is an important consideration when modelling the dispersion of atmospheric ammonia from intensive agricultural installations. The ventilation rate influences the full extent of the modelled plume of atmospheric ammonia in combination with the exit velocity. Currently, SCAIL-Agriculture presents a single ventilation rate for broilers, layers, sows, weaners and finishers. In reality, there is a much broader diversity of ventilation rates, which will influence any interpretation of predicted impacts based on models. Additional monitoring in combination with the proposed inventory would enhance knowledge of a more diverse array of usable ventilation rate factors. In this case, using the highest possible rate may underestimate concentrations near to the source; therefore, both the highest and lowest reported ventilation rates should be applied to model both the maximum dispersion extent and the maximum nearby concentration. This study also observed that newer ventilation systems are likely to have higher ventilation rates, which inevitably results in higher emission rates. Hence, newer systems with high ventilation rates

may reduce indoor concentrations of ammonia, benefiting animal and staff welfare at a cost of increasing the amount of ammonia leaving the building. Reduction measures currently being implemented by the EPA include pipe cooling and heat exchangers, which alter the ventilation and emissions from the animal houses.

- No poultry or pig house monitored was close to the lower BAT-AEL; this is was a result of the absence of ammonia emission reduction technology (with the exception of manure drying in the layer house). Both the broiler and layer emissions fell below the upper BAT-AEL, though the majority of emissions from pig housing exceeded this limit. Interestingly, most finisher houses fell below the upper limit, with the exception of the newest house, as highlighted previously. BAT conclusions identify a number of approaches to reduce ammonia emissions from housing, which are required most urgently on sow and weaner housing. Ironically, based on observed rates in this study, emission reductions for finisher housing are required more urgently on newer buildings than on older buildings.

6.2 Emission Reduction

- Emission reductions in IED-licensed pig and poultry farms will be sought through compliance with European Commission BAT conclusions (EU, 2017). These standards will be applied to all new and expanding licensed houses and will be applied to all existing houses by 2021. This decision from the EU identifies emission ranges that cannot be exceeded and offers suggestions for reduction techniques to comply with these values.
- Ammonia emission reduction for pig and poultry houses should be sought at the earliest possible point, i.e. the production of ammonia should be reduced rather than emission. Scrubbers can potentially reduce emissions by nearly 100%, but they are expensive and can sometimes be ineffective. Additionally, scrubbers reduce emissions from the building and do nothing to reduce concentrations indoors, which can influence animal welfare. An alternative method proposed by Koger *et al*. (2014) aptly states "[m]odern swine facilities have not been designed to maximize manure value nor to minimize ammonia emission"; they suggest an alternative pig farm design that incorporates manure belts to reduce emissions by 75%. This approach reduces concentrations indoors and allows for better control of emissions, both improving animal welfare and reducing environmental impacts. A similar approach was seen in the layer house that this study monitored, where manure was dried and removed weekly on conveyor belts and emissions and concentrations increase as the days progress. Increasing the frequency of manure removal would be an easily implemented control of ammonia emissions on this farm. It should be noted that, if an approach is not listed in the BAT conclusions, it is not considered BAT and must demonstrate its equivalence to another BAT technique.
- The UK Clean Air Strategy recommends a number of techniques that farmers can implement in order to reduce their ammonia emissions from animal housing and both the storage and spreading of slurry. These approaches should be adopted by Ireland with an aim of reducing both total emissions and local concentrations of ammonia. These approaches include the following: covering slurry stores; low-emission spreading techniques, i.e. trailing shoe or injection – even switching from splashplate to trailing shoe reduces emissions by 30%; incorporating manure into bare soil within 12 hours of spreading; cleaning animal collection points after use; reducing the protein content in animal diets; and switching from urea-based fertilisers to ammonium nitrate – which has lower emissions – or potentially using a urease inhibitor. Ireland needs to adopt these approaches to benefit its own national clean air strategy, which set more modest targets, encouraging emission reduction spreading technology and use of urease inhibitors or ammonium nitrate as fertiliser. Ireland needs to be ambitious in applications of reduction technologies across all agricultural sectors if the 2030 NEC Directive targets are to be met.

6.3 SCAIL-Agriculture

- Monitored rates show that SCAIL-Agriculture is broadly representative of poultry production. High rates from broiler production are probably being contributed to by high ambient concentrations from multiple nearby sources of ammonia. When rates are applied across the entire farm, the influence that underestimating sow and weaner emissions on total emissions becomes apparent, with both monitored pig farms in this study exceeding estimations generated using either EPA or SCAIL-Agriculture emission rates.

- This work also highlights the need for more detailed information relating to ventilation rates to be included in SCAIL-Agriculture to adequately assess the potential extent and scale of impacts on sensitive sites.
- Unlike the UK, which has access to detailed (1 × 1 km grid) ammonia concentration models, Ireland has relied on interpolated data from 1999 (de Kluizenaar and Farrell, 2000) and more recently monitored ambient concentrations from 2015 (Doyle *et al*., 2017). Predicting accurate background concentrations is vitally important when estimating potential impacts based on either critical levels or loads. In many cases, these may already be exceeded depending on the habitat type. There are three primary reasons why the interpolated data are not suitable concentration models and why care should be taken when interpreting the results of SCAIL-Agriculture models:
  – Interpolation type: when using empirical Bayesian kriging, the predicted concentrations at the monitoring points may not match the monitored concentration values. This can lead to both over- and underpredictions of concentrations depending on the area, as kriging is based on probabilistic – not deterministic – methods of interpolation.
  – High variability of emissions: it has been pointed out in the past that, on account of the high spatial variation of ammonia emissions, having only a limited number of concentration monitoring locations is not suitable for predicting national concentrations (Singles *et al*., 1998). Additionally, the 1999 survey monitored 40 locations and the 2015 survey only monitored 25, thereby further reducing the resolution of ammonia concentrations.
  – Monitoring locations: in both the 1999 and 2015 monitoring programmes, emphasis was placed on monitoring ambient concentrations. By design, monitoring was not conducted near intensive point sources of ammonia. Therefore, contributions from existing pig and poultry farms are completely excluded from the background concentrations in Ireland predicted by SCAIL-Agriculture.
  – Cumulative impacts: use of any modelled ambient concentration including FRAME and MARSH does not adequately contribute to the assessment of cumulative impacts on Natura 2000 sites as required under the Habitats Directive. As hotspot sources have varying emission and ventilation rates, with varying dispersion extents, multiple hotspot sources near to each other will need to be assessed "in combination" during modelling in order to comply with this requirement of the Habitats Directive.

6.4 Ecological Impacts

- Dispersion modelling from monitored poultry and pig farms indicates that concentrations could potentially be as high as 8 μg NH_3 m^{-3} within 146, 129 and 581 m of Broiler Farm, Layer Farm and Pig Farm 2, respectively, when ambient concentrations are included (slurry stores and other hotspot sources are excluded). These distance thresholds are of importance, as 8 μg NH_3 m^{-3} was the concentration monitored on Moninea Bog in Northern Ireland and this had very serious acute impacts.
- Contributions from Broiler Farm, Layer Farm and Pig Farms 1 and 2 to NH_3 concentrations exceeded the lower critical level of 1 μg NH_3 m^{-3} within 432, 399, 800 and 1685 m and the higher critical level of 3 μg NH_3 m^{-3} within 187, 172, 389 and 684 m, respectively. The dispersion potential of farms is especially important when considering cumulative impacts on Natura 2000 sites. This is determined by a combination of emission rates, ventilation rates, meteorology and topology. Overlapping dispersion plumes from hotspot sources are likely to contribute to cumulative impacts on Natura 2000 sites.
- Thresholds for cumulative impacts and requirement of detailed dispersion modelling in Ireland and the UK are set at 4% and 1% (depending on regulatory body) of critical levels. Modelled concentrations of 0.12 μg NH_3 m^{-3} (4% of 3 μg NH_3 m^{-3}) occurred 2.2, 2.1, 4.4 and 7.6 km downwind of Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively. Concentrations of 0.04 μg NH_3 m^{-3} (4% of 1 μg NH_3 m^{-3}) were modelled within 10.4, 6.5, 10.4 and 20.1 km of Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively. The stricter 1% of critical levels

were modelled to occur within 14.6, 7.1, 13.3 and 24.7 km for 3 μg NH_3 m^{-3} and 32.6, 28.6, 30.5 and 50.9 km for 1 μg NH_3 m^{-3} for Broiler Farm, Layer Farm and Pig Farms 1 and 2, respectively.

- The MARSH risk modelling, inclusive of cattle, sheep, pigs, poultry and synthetic fertiliser, indicates that 389 SACs and 142 SPAs may exceed a concentration of 1 μg NH3 m^{-3}, 161 SACs and 65 SPAs may exceed a concentration of 2 μg NH_3 m^{-3}, and 25 SACs and 14 SPAs may exceed a concentration of 3 μg NH_3 m^{-3}. Concentrations from this model were underestimated when compared with monitored concentrations.
- Ambient monitoring of atmospheric ammonia on Natura 2000 sites is an effective method to identify the risk posed to individual sites. This should be coupled with ecological indicator monitoring on sites in future, to comply not only with the Habitats Directive but also with the NEMN, which is currently required under the NEC Directive.
- Further ecological monitoring targeting indicators of ammonia pollution needs to be carried out; this could feature as a component of the NEMN required by the NEC Directive. Surveying the 12 Natura 2000 sites monitored by this project could act as a baseline for impacts across a range of predicted concentrations. Linking ecological monitoring with concentration monitoring and MARSH modelling would enhance the model's predictions across Ireland and Northern Ireland.
- Impacts observed at Raheenmore Bog SAC will contribute to its inability to meet its conservation objectives. As the impacts on this site probably come from neighbouring cattle farming and slurry spreading, greater attention needs to be given to these sources of ammonia and their contribution to impacts on Natura 2000 sites.
- The passive monitoring of atmospheric ammonia on Natura 2000 sites was primarily based on ranger availability and not on the level of risk of the site. It acted as a means to trial the collaboration of NPWS staff as part of an ammonia monitoring programme on sensitive sites. The AmmoniaN2K project recommends continuing this work on further "at-risk" sites within the Natura 2000 network. These data should be integrated into site-specific nitrogen management plans for every "at-risk" Natura 2000 site, where strategies can be put in place to reduce the impacts of atmospheric ammonia. These data should be used to enhance the long-term atmospheric ammonia programme recommended by Doyle *et al*. (2017).
- Site-specific nitrogen management plans need to be developed for Natura 2000 sites at risk from atmospheric ammonia, identifying contributing sources and working with local farmers to manage both emissions and their local impacts. Ammonia emission management plans need to be implemented across all farms in the country in order to reduce national emissions. These could incorporate methods for reducing nearby ammonia sources or restrict certain activities nearby (slurry spreading). Further restrictions may limit the development of new farms proximal to certain Natura 2000 sites.

6.5 Policy

- The use of distance thresholds is a useful mechanism for early first-stage screening of potential impacts to Natura 2000 sites. Modelling dispersion plumes from both pig and poultry farms showed that for most farms 10 km is sufficiently precautionary to protect Natura 2000 sites from impacts of atmospheric ammonia. However, as the modelled dispersion plumes from the second pig farm significantly extended beyond 10 km, de minimis deposition values were not met until 20 km from the farm. Caution should therefore be applied to the use of such simple screening measures, and the use of screening tools such as SCAIL-Agriculture may be necessary even if the farm is 20 km from a potentially sensitive Natura 2000 site. Distance thresholds used internationally, specifically in the UK, vary significantly across the UK, with Northern Ireland using 7.5 km, Scotland and Natural England 10 km, and the Environment Agency in England and Natural Resources Wales using 5 km. Modelling from this study suggests that, when the lower distance thresholds are applied, the assessment excludes potential deposition across woodlands (higher deposition velocity) and may not adequately represent the farm's contribution to cumulative impacts.
- Additionally, the modelled affected area varied from year to year depending on meteorological data, highlighting the importance of modelling

using multiple years of meteorological data when carrying out detailed dispersion modelling to predict potential impacts on Natura 2000 sites. This project also recommends modelling both the year with the maximum dispersion potential and the year with the lowest in order to account for potential underestimates of both extent and nearby concentration.

- Incorporating below-threshold units when assessing the risk of cumulative impact from intensive agricultural installations significantly increases the associated risk. Additionally, with increasing cattle herds and increased amounts of slurry being spread, it is vitally important that these sources of ammonia are also assessed. The worst affected areas based on the modelling and monitoring work undertaken as part of this project are County Monaghan, east County Cavan and west County Limerick. These three counties are also those most likely to be affected by cumulative impacts from atmospheric ammonia arising from intensive agriculture units.
- It is important that unlicensed, below-IED threshold facilities are considered in future on account of their contribution to cumulative impacts of atmospheric ammonia. Additionally, inclusion of other sources of both nitrogen and ammonia should be considered for cumulative impacts on Natura 2000 sites. This should include grazing cattle, cattle housing, slurry spreading and traffic. The AmmoniaN2K project recommends collaboration between the Department of Agriculture, Food and the Marine (DAFM), the Department of Communications, Climate Action and Environment and the EPA in future to share information on ammonia sources. In order to assess cumulative impacts in line with the Habitats Directive, any future project researching ammonia concentrations will need access to the DAFM's database of farm locations. This inventory would allow for more accurate dispersion, concentration and deposition models to be created. This would better inform relevant stakeholders when assessing background concentrations of atmospheric ammonia and current exceedances and better inform future planning applications. Additionally, environmental permitting recommended by the UK Clean Air Strategy for cattle farms should be considered in Ireland.
- Detailed atmospheric dispersion modelling of pig and poultry farms within at least 5 km of Natura 2000 sites is required in order to accurately determine the potential impacts on the site. Modelling conducted by the AmmoniaN2K project prioritised risk modelling, which is not representative of actual potential impacts.
- Ireland currently has a "National Air Pollution Control Programme", which highlights a number of approaches to reduce national emissions, including the following:
  - reducing the splashplate spreading and increasing the uptake of trailing hose and shoe spreading techniques;
  - introducing an altered timing management system (ATMS) for cattle manure spreading, which permits spreading only when the weather and time of day result in a reduced potential for emissions;
  - using urea stabilisers;
  - manure drying for poultry;
  - covering of outdoor manure stores for cattle and pigs;
  - adding alum to poultry litter;
  - reducing crude protein in diets of pigs;
  - using the Code of Good Agricultural Practice to reduce ammonia emissions.
- If implemented, these approaches to reduce ammonia emissions can significantly contribute to reducing total national emissions and reducing potential impacts on sensitive habitats, enhancing Ireland's compliance with the NEC Directive, the Habitats Directive and BAT. In 2019, the UK published its final Clean Air Strategy (Department for Environment, Food & Rural Affairs, 2019); this guidance highlights the following additional points that could be considered for emission management in Ireland:
  - Develop environmental land management system to protect habitats.
  - Reduce ammonia on sensitive Natura 2000 sites by 17% by 2030.
  - Monitor impacts of air pollution on natural habitats – report annually.
  - Extend environmental permitting to cattle farming (already done in Northern Ireland).
- A 2019 judgment from the European Court of Justice clarifies that fertiliser spreading and grazing qualify as "projects" for assessment under the Habitats Directive in order to preserve Natura

2000 sites (cases C 293/17 and C 294/17) (EU, 2019). This judgment intended to cover existing practices, as the Netherlands was found to be non-compliant and not adequately carrying out assessments for these practices. This judgment specifies that all slurry-spreading and grazing practices proximal to Natura 2000 sites need to be assessed under the Habitats Directive. A detailed analysis of this case law is required in order to develop an assessment process by which grazing cattle and land spreading of slurry can be assessed. There is no current legal instrument by which these assessments can be currently carried out in Ireland. This could potentially require the extension of controls beyond the boundary of Natura 2000 sites in order to adequately protect sensitive habitats therein.

6.6 Future Work

- Following intensive monitoring from this project, a minimum monitoring time could be developed using data collected and used to inform an extensive monitoring programme of intensive pig and poultry farms. BAT conclusions allow farms to use emission factors or monitoring to calculate their ammonia emissions. Further monitoring will help clarify the diversity of emission rates and also assist farmers in BAT compliance.
  - Additional monitoring of houses in multiple locations would benefit from understanding the influence of local ambient concentrations on emission rates.
  - The influence of age, design type, slurry storage, ventilation type, floor type, etc., on emission rates needs to be further investigated in order to develop site-specific emission rates.
- Ireland urgently requires a detailed source-apportioned concentration map, similar to FRAME used in the UK. The MARSH modelling conducted was intended to create a risk map of areas likely to be affected by atmospheric ammonia, acting as a step towards a detailed concentration model. In order to accurately determine potential impacts on Natura 2000 sites from atmospheric ammonia, a new concentration model is required. This would, in addition, improve deposition modelling undertaken as part of EMEP reporting. The inclusion of unlicensed facilities and detailed recent information on cattle numbers and locations would enhance this model in the future. Estimates for areas in receipt of slurry being spread also need to be improved. The UK Centre for Ecology & Hydrology has in the past used FRAME to model atmospheric ammonia concentration and deposition in Ireland (Fournier *et al.*, 2002), which could be replicated using the relevant detailed information.
- The MARSH risk map produced in this project could potentially be used to assess the impact of dry reduced nitrogen deposition on Natura 2000 sites. This map predicts likely concentrations of atmospheric ammonia using best available information and is therefore the most representative concentration map currently available. This modelling would ideally follow an update to currently used deposition velocities recommended in Doyle *et al.* (2017), but an indicative model could be produced before then.
- The critical levels of $3\,\mu g\,NH_3\,m^{-3}$ and $1\,\mu g\,NH_3\,m^{-3}$ used in this study are international standards that have been shown to vary depending on the habitat and temperature. Research is needed to test the appropriateness of these critical levels in Ireland. Echoing the recommendation made by Aherne *et al.* (2017), this could be paired with a study investigating the impacts of nitrogen deposition on semi-natural habitats in Ireland.
- Further research is required to establish the contribution of intensive point sources, such as IED facilities, to long-range particulate ammonium pollution and their subsequent contribution to wet deposition of nitrogen. This would probably require the creation of detailed dispersion and transformation models of ammonia from intensive units, which should be integrated into national concentration and deposition models of nitrogen in Ireland. The AmmoniaN2K project focused on predicting impacts from ammonia, not ammonium. This is likely to have transboundary impacts because of the density of poultry houses in County Monaghan and prevailing south-westerly winds. Cattle and slurry spreading are also potential contributors to transboundary effects. However, emissions from these sources are less likely to spread as far as those from pig and poultry farms, as houses are primarily naturally ventilated and both slurry and grazing cattle are diffuse sources of ammonia. It is unclear how different sources contribute to ammonium deposition and

how far it spreads from each specific source and what sources in particular are problematic for transboundary impacts.

- Research is required to establish any potential link with atmospheric ammonia and ammonium on human health in Ireland. International research has made links to the early onset of asthma in children; based on the prevalence of asthma in Ireland, this needs to be given consideration as a potential contributing source. As Ireland's ammonia concentrations are lower than in countries with higher stocking rates where much of this research was carried out (e.g. Denmark, the Netherlands and Germany), the relationship needs to be further researched and links to human health impacts in Ireland clarified.
- Similar to the EPA report *Development of Critical Loads for Ireland: Simulating Impacts on Systems (SIOS)* (Aherne *et al*., 2017), the AmmoniaN2K project also recommends a wider integration of critical levels and critical loads into national policy assessments. Specifically for AA under the Habitats Directive, an assessment of contributions from all existing hotspot sources has not yet been carried out and neighbouring sources are not usually considered when applying for new farms. If new developments contribute to an exceedance of critical levels, they should demonstrate adequate technology to reduce their emissions to a point where critical levels are not exceeded. Guidance for agricultural and ecological consultants needs to be written, and up-to-date concentration models are needed. Modelling the contributions from existing farms will highlight areas where new farms can be built.
- In the UK, a website detailing every conservation feature on every Natura 2000 site, and the associated critical levels and loads, is available for anyone wishing to assess impacts on the sites (Air Pollution Information System, APIS) (UK Centre for Ecology & Hydrology, 2016). A similar website should be created for Ireland; alternatively, APIS is open to extending its website to include Ireland (S. Bareham, Natural Resources Wales, 16 January 2019, personal communication). Further guidance needs to be provided to ecologists who assess impacts on a regular basis, in addition to providing the information on site sensitivity; this needs to be formulated to ensure ammonia impacts are adequately assessed by consultants.
- The AmmoniaN2K project focused on emission and impacts specifically from atmospheric ammonia; work presented in this report did not consider its contribution to either total or reduced nitrogen deposition. Though the dominant form of reduced nitrogen deposition in Ireland is from dry deposition of ammonia (Doyle *et al*., 2017), impacts on Natura 2000 habitats should be considered in combination with wet deposition of ammonium and other forms of nitrogen. Any assessment of impacts in the future should take cognisance of all contributing forms of nitrogen, in addition to the recently highlighted species change points (Wilkins *et al*., 2016a).
- The BAT conclusions published in February 2017 (EU, 2017) and the supporting BAT reference documents published in July 2017 (Giner Santonja *et al*., 2017) specify AELs for pig and poultry farms to be implemented on all new licensable activities from February 2017 and on all existing licensed farms by February 2021. Both offer emission mitigation approaches legally required to reduce ammonia emissions from licensed pig and poultry farms. The conclusions specify that additional measures should be utilised to reduce emissions, provided that the AELs are met. Applying recommendations outlined in the NAPCP for pig and poultry facilities will enhance the reductions sought through BAT, improving both emissions from housing and subsequent slurry spreading.

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Abbreviations

AA	Appropriate assessment
ADMS	Atmospheric Dispersion Modelling System
AEL	Ammonia emission level
AER	Annual Environmental Report
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
ALPHA	Adapted Low-cost Passive High Absorption
APIS	Air Pollution Information System
AWI	Area Weighted Indicator
BAT	Best available techniques
CIGR	Commission Internationale du Génie Rural (or International Commission of Agricultural Engineering)
CLRTAP	Convention on Long-range Transboundary Air Pollution
CORINE	Coordination of Information on the Environment
DAFM	Department of Agriculture, Food and the Marine
DAMOS	Danish Ammonia Modelling System
DELTA	Denuder for Long-term Atmospheric (sampling)
DWI	Designation Weighted Indicator
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
EU	European Union
FRAME	Fine Resolution Atmospheric Multi-pollutant Exchange
IED	Industrial Emissions Directive
LDPE	Low-density polyethylene
LGR	Los Gatos Research
MAN	Measuring Ammonia in Nature
MARSH	Mapping Ammonia Risk on Sensitive Habitats
NAPCP	National Air Pollution Control Programme
NEC	National Emissions Ceilings (Directive)
NEMN	National Ecosystem Monitoring Network
NPWS	National Parks and Wildlife Service
OA-ICOS	Off-axis Integrated Cavity Output Spectroscopy
PRTR	Pollutant Release and Transfer Register
SAC	Special Area of Conservation
SCAIL	Simple Calculation of Atmospheric Impact Limits
S.I.	Statutory Instrument
SPA	Special Protection Area
TITAN	Threshold Indicator Taxa Analysis
UCD	University College Dublin
UNECE	United Nations Economic Commission for Europe

Glossary

AmmoniaN2K	Project title where N2K represents Natura 2000
Broiler	Chicken raised for meat production
Farrowing sow	Term given to lactating sow, usually housed with piglets
Finisher	Final stage of pig production cycle focused on weight gain (> 30 kg as classified by the IED)
iTX	Chemiluminescent ammonia analyser
Layer	Chicken raised for egg production
Natura 2000	Sites designated under the EU Habitats (92/43/EEC) and Birds Directives (2009/147/EC)
Weaner	Young pig after removal from farrowing house

Appendix 1 Project Outputs

A1.1 Peer-reviewed Publications

Kelleghan, D., Hayes, E., Everard, M. and Curran T.P., 2019. Mapping ammonia risk on sensitive habitats in Northern and the Republic of Ireland. *Science of the Total Environment* 649: 1580–1589.

Three additional papers detailing monitoring and modelling for farms have been prepared for submission, in addition to a single paper detailing monitoring on Natura 2000 sites.

A1.2 Non-peer-reviewed Publications and Conferences and Workshops

Available to download separately from the UCD Research Repository (https://researchrepository.ucd.ie/).

Appendix 2 Daily Average Emission Rates

The following appendices detail the 2 years of monitoring (2015–2017) as a single year in order to best represent the seasonal and daily variation of emissions from the pig and poultry houses monitored.

Figures detailing averaged daily emission rates for each house monitored are available to download separately from the UCD Research Repository (https://researchrepository.ucd.ie/).

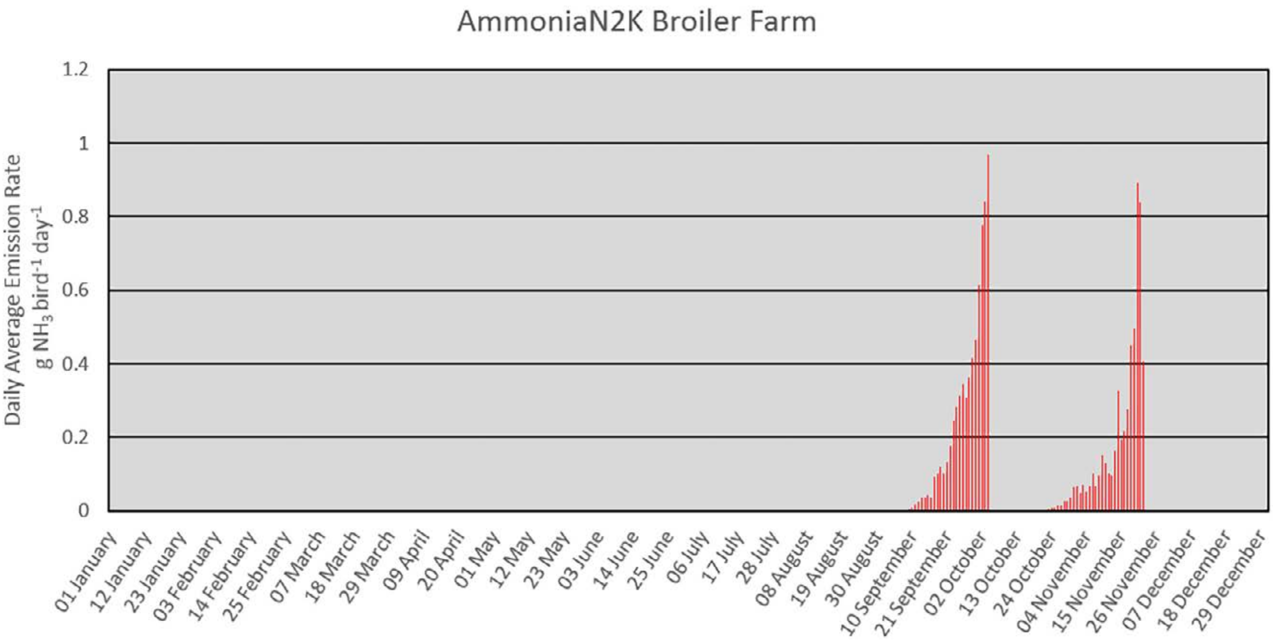

Figure A2.1. Example averaged daily emission rates available to download for each house monitored.

Appendix 3 Natura 2000 Site Risk Table

Here we detail site-specific information for Ireland for 2018:

1. critical level of SAC or SPA, based on most sensitive conservation feature;[1]
2. the number of pig and poultry farms above and below the IED threshold within 10 km of each site;
3. the percentage of the site within each MARSH risk category;
4. the percentage of the site within each Nitroindex risk category.

Spreadsheet “Northern Ireland” details the percentage of each SAC and SPA within each MARSH and Nitroindex risk category.

Sites are ranked, based on largest proportion of the site exposed to the highest risk values, primarily by MARSH and secondarily by Nitroindex.

Table A3.1. Example of facility data

Site name	Country	Critical level (μg m^{-3})	Total area	No. of facilities within 10 km				
				Licensed pig	Unlicensed pig	Licensed poultry	Unlicensed poultry	Total
Clonakilty Bay SAC	ROI	1	508	1	7	1	7	16
Courtmacsherry Estuary SAC	ROI	3	735.4	1	10	0	7	18
Slaney River Valley SAC	ROI	1	6009.5	5	0	0	0	5
Lower River Suir SAC	ROI	1	7079.8	18	42	0	7	67
Blackwater River (Cork/Waterford) SAC	ROI	1	10142.7	13	27	15	58	113
River Boyne And River Blackwater SAC	ROI	1	2315.8	11	21	4	23	59

Table A3.2. Example of MARSH and Nitroindex data

Site name	Percentage of site (%)								
	MARSH 0–1	MARSH 1–2	MARSH 2–3	MARSH 3–4	MARSH 4–5	Nitroindex −1.0 to −0.5	Nitroindex −0.5 to 0.0	Nitroindex 0.0 to 0.5	Nitroindex 0.5 to 1.0
Clonakilty Bay SAC	0	2.8	15.1	41.5	0	0	0	59.1	1
Courtmacsherry Estuary SAC	0	0	16.5	38.8	0	0	0	0	55.8
Slaney River Valley SAC	0	3.3	24.6	16	0	3.3	29.8	10.9	0.1
Lower River Suir SAC	0	34.4	61.3	4.2	0	1	38.2	57.4	3.3
Blackwater River (Cork/Waterford) SAC	0	55.4	41	2.5	0	0	6.2	56.4	36.4
River Boyne And River Blackwater SAC	0	32.4	66.4	1.2	0	0	1.4	72.5	26.1

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1 For SPAs this refers to the percentage of habitats within the SPA that are likely to have a critical level of 1 μg m^{-3} based on CORINE habitat mapping. This is relevant to the conservation objectives of SPAs whereby it is sought that “the natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future” and “there is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis”.

Appendix 4 Natura 2000 Site Summary and Sensitivity

Table A4.1. Here we detail SACs' qualifying features and their critical levels (based on the UK's Air Pollution Information Service)

Site name	N2K code	Annex I habitat/Annex II species	Sensitive to N?	Critical level
Achill Head	IE0002268	Large shallow inlets and bays [1160]	No	3
Achill Head	IE0002268	Mudflats and sandflats not covered by seawater at low tide [1140]	Yes	3
Achill Head	IE0002268	Reefs [1170]	No	3
Akeragh, Banna and Barrow Harbour	IE0000332	Fixed coastal dunes with herbaceous vegetation (grey dunes) [2130]	NA	3
Akeragh, Banna and Barrow Harbour	IE0000332	Annual vegetation of drift lines [1210]	No	3
Akeragh, Banna and Barrow Harbour	IE0000332	Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*) [1330]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	Embryonic shifting dunes [2110]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	Humid dune slacks [2190]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	Mediterranean salt meadows (*Juncetalia maritimi*) [1410]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	*Salicornia* and other annuals colonising mud and sand [1310]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes) [2120]	Yes	3
Akeragh, Banna and Barrow Harbour	IE0000332	European dry heaths [4030]	Yes	1
All Saints Bog and Esker	IE0000566	Active raised bogs [7110]	Yes	1
All Saints Bog and Esker	IE0000566	Bog woodland [91D0]	Yes	1
All Saints Bog and Esker	IE0000566	Degraded raised bogs still capable of natural regeneration [7120]	Yes	1
All Saints Bog and Esker	IE0000566	Depressions on peat substrates of the Rhynchosporion [7150]	Yes	1
All Saints Bog and Esker	IE0000566	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*) (important orchid sites) [6210]	Yes	1

NA, not applicable.

Available to download separately from the UCD Research Repository (https://researchrepository.ucd.ie/).

Appendix 5 MARSH and Nitroindex Shapefiles

Available to download separately from the UCD Research Repository (https://researchrepository.ucd.ie/).

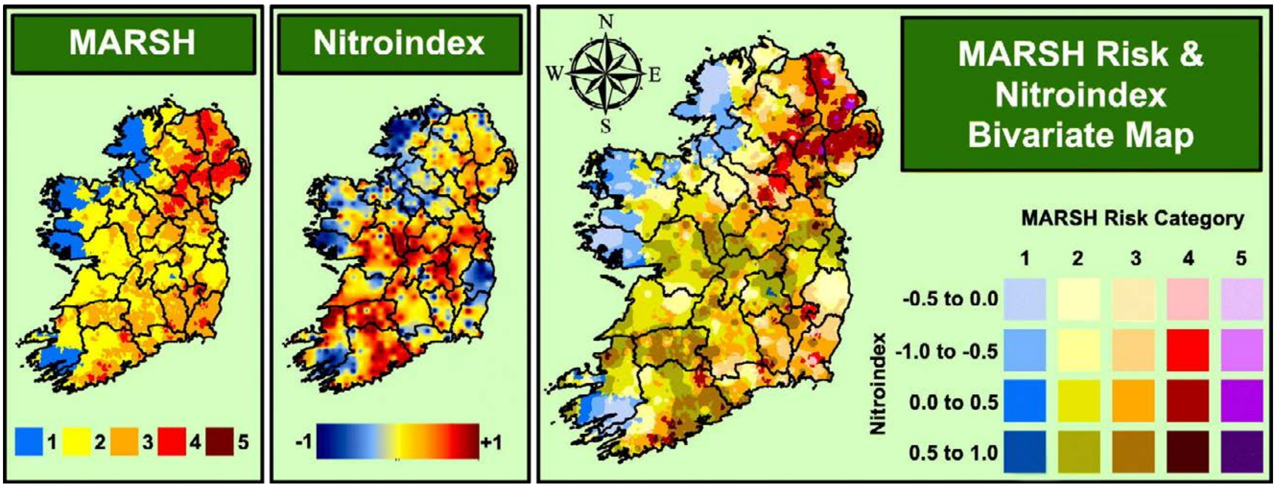

Figure A5.1. MARSH and Nitroindex maps of Ireland. Extracted from Kelleghan *et al*. (2019).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 347

Assessment of the Impact of Ammonia Emissions from Intensive Agriculture Installations on Special Areas of Conservation and Special Protection Areas

Authors: David B. Kelleghan, Enda T. Hayes, Mark Everard and Thomas P. Curran

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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

Atmospheric ammonia poses a significant threat to biodiversity and human health around the world. A high concentration can result in significant changes to the structure of ecosystems, as atmospheric ammonia is particularly harmful to a number of nitrogen-sensitive habitats (bogs, heath, semi-natural grasslands, etc.). In addition, ammonia reacts with other pollutants in the air to form particulate matter, which disperses over great distances. Atmospheric particulate matter has been linked to a range of pulmonary and cardiac issues in humans. Concentrations of ammonia in the air downwind of hotspot sources, such as pig and poultry farms, are likely to negatively affect the environment. The contribution of multiple sources of ammonia to cumulative impacts in Ireland is currently poorly understood.

Informing Policy

The AmmoniaN2K project aimed to assist the EPA licensing of intensive agriculture installations (pig and poultry farms) in Ireland. This work is particularly relevant to appropriate assessments on Natura 2000 sites under the Habitats Directive (92/43/EEC), where modelling of contributions from agricultural sources is required. Emission rates generated and recommendations from detailed monitoring will support future assessments. The identification of farms below the Industrial Emission Directive (2010/75/EU) threshold will also assist the required cumulative impact assessments under appropriate assessment. This information has also aided the spatial reporting of emissions, which has benefited European Monitoring and Evaluation Programme concentration and deposition modelling. The emission rates generated can be used to validate and inform the Pollutant Release and Transfer Register reporting of national emissions in Ireland. Improving inventory reporting is a vital step to ensure compliance with limits set under the National Emissions Ceilings Directive (2016/2284/EU) –Ireland currently exceeds its ammonia emission limit under this directive. Monitoring on Natura 2000 sites has highlighted the need for alternative agricultural practices to reduce this impact.

Developing Solutions

The AmmoniaN2K project quantified and assessed the impact of ammonia emissions from intensive pig and poultry units on Natura 2000 sites in Ireland. This was done by monitoring detailed ammonia emissions from 17 animal production houses across four farms. These rates are compared with best available techniques-ammonia emission levels (BAT-AELs), past monitoring in Ireland and recommended rates by Simple Calculation of Atmospheric Impact Limits (SCAIL-Agriculture). Dispersion modelling of all farms was conducted using monitored rates to identify distance downwind from where both impacts and estimated minimum contributions occurred. An approach to identify farms below the Industrial Emission Directive (2010/75/EU) threshold was developed, in order to identify the total number of intensive agriculture units that are proximal to Natura 2000 sites. The Mapping Ammonia Risk on Sensitive Habitats (MARSH) model, developed as part of this study, assigned a risk of impacts from all sources of ammonia (including cattle and sheep) to Natura 2000 sites in Ireland. This model was checked against monitoring on Natura 2000 sites, which also identified potential impacts at these locations.

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