The impact of ammonia emissions from agriculture on biodiversity

An evidence synthesis

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Preface

This report provides a synthesis of the existing evidence on the impacts of ammonia emissions from agriculture on biodiversity and the possible interventions to reduce emission levels. The review was conducted in 2018 by RAND Europe, working in collaboration with the Royal Society. The study was funded by the Royal Society. The document should be of use to policymakers and others interested in understanding the current status of the evidence around ammonia emissions, their impact on biodiversity, potential interventions to reduce emissions and their effectiveness, and costing of both harms of emissions and interventions to reduce emissions.

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Summary

As levels of other air pollutants have declined, ammonia emissions in the UK have been rising since 2013, with significant implications for biodiversity and human health. The agricultural sector is the biggest contributor to ammonia pollution, producing 82 per cent of all UK ammonia emissions in 2016. The aim of this study is to provide an overview of the existing evidence in three main areas:

- The impacts of ammonia emissions from agriculture on biodiversity in the UK.
- The interventions available to reduce ammonia emissions from agriculture and their effectiveness.
- The costs of the interventions, and how these compare to the costs of inaction on ammonia emissions, both in terms of impacts on biodiversity and wider impacts (e.g. on human health).

Impact of ammonia on biodiversity

Ammonia itself and the nitrogen deposition resulting from ammonia emissions negatively affect biodiversity. Ammonia is one of the main sources of nitrogen pollution, alongside nitrogen oxides. A major effect of ammonia pollution on biodiversity is the impact of nitrogen accumulation on plant species diversity and composition within affected habitats. Common, fast-growing species adapted to high nutrient availability thrive in a nitrogen-rich environment and out-compete species which are more sensitive, smaller or rarer. Ammonia pollution also impacts species composition through soil acidification, direct toxic damage to leaves and by altering the susceptibility of plants to frost, drought and pathogens (including insect pests and invasive species). At its most serious, if changes in species composition and extinctions are large, it may be that remaining vegetation and other species no longer fit the criteria for that habitat type, and certain sensitive and iconic habitats may be lost.

Certain species and habitats are particularly susceptible to ammonia pollution. Bog and peatland habitats are made up of sensitive lichen and mosses which can be damaged by even low concentrations of ammonia. Grasslands, heathlands and forests are also vulnerable. However, much of the wider evidence on biodiversity impacts relates to all nitrogen pollution, rather than just ammonia.

There is far less evidence on the impact of ammonia, and nitrogen more generally, on animal species and the wider ecosystem. However, animal species depend on plants as a food source; therefore herbivorous animals are susceptible to the effects of ammonia pollution. There is a negative correlation between flower-visiting insects, such as bees and butterflies, and nitrogen pollution. Ammonia affects freshwater ecosystems through direct agricultural run-off leading to eutrophication

(accumulation of nutrients, leading to algal growth and oxygen depletion) and also has toxic effects on aquatic animals that often have thin and permeable skin surfaces.

Quantifying the economic impact of ammonia emissions on biodiversity is challenging and the methods used are subject to debate. Available estimates suggest that loss of biodiversity due to ammonia emissions could have impacts in the UK which can be valued, conservatively, at between £0.20 and £4 per kg of ammonia. Combining this with the monetised health impacts, our conservative estimate of the total costs from both health and biodiversity impacts of ammonia in the UK is £2.50 per kg of ammonia (though the range of possible values is from £2 to £56 per kg). This conservative estimate, combined with projected emission data, suggests that if no action is taken to reduce ammonia emissions, the negative impacts on the UK in 2020 could be equivalent to costs of over £700m per year. However, there are significant uncertainties in these values. The range of possible costs, based on the estimates in the literature and best available projections for emissions, are between £580m and £16.5bn per year.

Reducing ammonia emissions

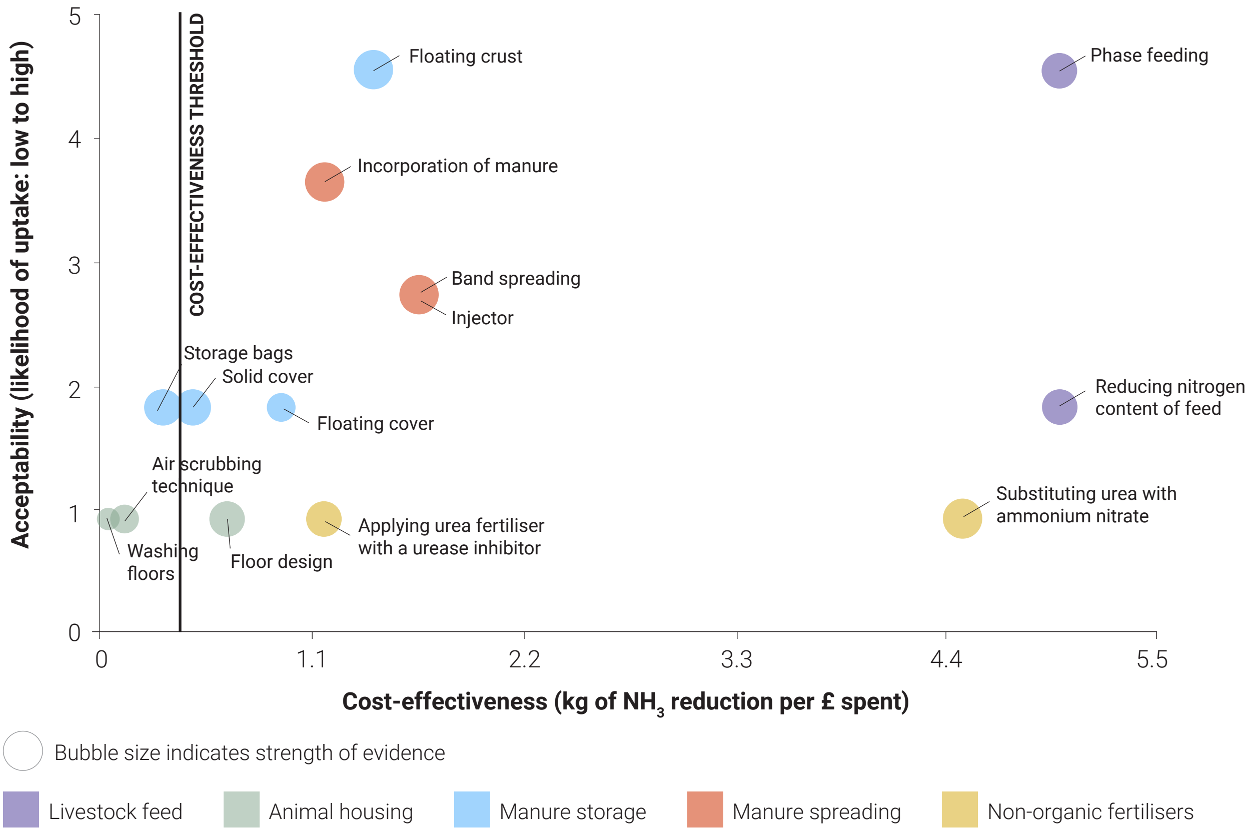
Ammonia emissions can be reduced by managing the production, storage and spreading of manure. Some of the most established ways to do this are summarised in Table 1. Figure 1 provides an overview of the cost-effectiveness, acceptability and strength of evidence for a range of specific interventions. Based on our estimates above, the impacts of ammonia can be conservatively costed at £2.50 per kg, which is equivalent to £1 of damage being caused by every 0.4kg of ammonia emitted. On this basis, any intervention which exceeds this threshold – to the right of the line in Figure 1 – could be considered cost-effective, which would include the majority of interventions. However, the whole ammonia lifecycle needs to be taken into account. If emissions are reduced immediately after manure production (e.g. through collection), but then not reduced in later stages (e.g. in storage or in spreading), then the emissions benefits at earlier stages are negated. Therefore, interventions need to be used in combination, spanning the whole lifecycle of manure production, storage and application. This also highlights the benefits of feed-based approaches which reduce the amount of ammonia produced in manure in the first place. It is also important to consider the interplay of ammonia emissions with those of other polluting gases, which might be negatively affected by some interventions, or by ammonia reductions generally. For example, excess nitrogen, whilst reducing species richness, can increase the volume of plant matter overall, which has benefits for carbon sequestration.

From a policy perspective, a mix of regulation, incentives and education are likely to be necessary to support the implementation of interventions. Evidence from the Netherlands and Denmark suggests that for interventions with a high level of acceptability to the agricultural sector, regulatory approaches can be introduced fairly quickly to support compliance. Where there are high upfront costs for farms, or a lower level of acceptability or knowledge, there may be more need for incentives and education, alongside voluntary actions in the first instance, before regulation can be effectively introduced. It may also be that different approaches are needed across different farm types or sizes. Wider education and awareness-raising may also be needed to help build understanding of the importance and costs of ammonia reduction amongst the public and in the retail sector, so that the full cost of these measures are not placed solely on the agricultural sector and/or government subsidies.

Table 1. Summary of categories of interventions to reduce ammonia emissions

Method	Description	Reduction in ammonia emissions	Limitations	Implementation cost (£/kg of ammonia)
Livestock feed	Reducing the amount of excess protein in livestock diets	10% to 60%	Higher feeding costs to farmers and potential for imbalanced nitrogen levels in the farm as the full use of grass production is not guaranteed	-2.3 to 2.3
Animal housing	Designing animal housing to better contain manure and reduce emissions	10% to 90%	High investment costs to refurbish or replace existing buildings	1 to 27
Manure storage	Storing manure for spreading as fertiliser in ways that reduce emissions	30% to 100%	Difficult to mix covered slurry; different covers are suitable for different quantities	0.4 to 3
Manure spreading	Methods for spreading manure as fertiliser that reduce emissions	0% to 99%	Effectiveness varies	-0.6 to 2.3
Non-organic fertilisers	Using manufactured fertilisers in ways that reduce emissions	40% to 90%	Ammonia emissions from organic fertilisers in the UK only account for a small proportion (c.10%) of ammonia emissions	-0.6 to 2.3

Figure 1. Bubble diagram showing strength of evidence, cost effectiveness and acceptability for a range of interventions to reduce ammonia emissions



Source: RAND Europe analysis. Cost-effectiveness and strength of evidence from Bittman et al. (2014). Acceptability based on likelihood of uptake from low (1) to high (5) as set out in Newell Price et al. (2011).

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Abbreviations and glossary

$\mu g\ m^{-3}$	Micrograms per cubic metre
Acidification	The process by which the soil or water pH decreases over time
CBED	Concentration-based estimates of deposition
CH_4	Methane, a gas that is naturally produced from livestock farming and other wetland farming conditions
CPI	Consumer Price Index
Defra	Department for Environment, Food & Rural Affairs
Deposition	The process by which ammonia is removed from the atmosphere and reaches the ground
Dry deposition	Ammonia is removed from the atmosphere through contact with the surface of plants or the ground, or through interacting with a particle that subsequently falls to the ground
Ecosystem services	The benefits provided by ecosystems that contribute to making human life both possible and worth living
Eutrophication	Excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life and a depletion of oxygen
N_2	Di-nitrogen
N_2O	Nitrous oxide, a colourless gas produced as part of the nitrogen cycle
Natural Capital	The world's stocks of natural assets which include geology, soil, air, water and all living things
NECD	National Emission Ceilings Directive
NH_3	Ammonia, a colourless gas which is both naturally occurring and manufactured
NH_4	Ammonium
NO	Nitric oxide, a colourless gas produced as part of the nitrogen cycle
NO_2	Nitrite

NO_3	Nitrate
NOx	Nitrogen oxides
PHE	Public Health England
PM	Particulate Matter
UNECE	United Nations Economic Commission for Europe
Volatilisation	The evaporation of substances at normal temperatures
VOLY	Value of Life Years Lost
WHO	World Health Organization
Wet deposition	Ammonia is dissolved into water vapour and returns to the land surface as rain
Willingness to pay	The maximum amount someone is willing to pay for something in order to result in a favourable result or avoid an unfavourable result

Acknowledgements

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1 Introduction

The aim of this report is to synthesise the existing evidence on the impacts of ammonia emissions from agriculture on biodiversity. The work focuses on three main questions:

1. What are the impacts of ammonia emissions from agriculture on biodiversity in the UK?
2. What interventions are available to reduce ammonia emissions from agriculture, and how effective are they?
3. How do the costs of implementing those interventions compare to the costs of inaction on ammonia emissions, both in terms of impacts on biodiversity and wider impacts (e.g. on human health)?

The report provides a summary of the existing evidence, the gaps in evidence, as well as caveats, limitations and complexities. The report is likely to be useful for policymakers and others looking to develop an overview of the existing knowledge on this topic. The work is focused on the UK context, but much of the evidence is likely to be more widely applicable.

In the remainder of this chapter we provide an introduction to ammonia pollution, its impacts, and the policy context. Chapter 2 describes the effects of ammonia on biodiversity and the costs of inaction. Chapter 3 sets out possible interventions, their effectiveness and costs. In Chapter 4 we reflect on the findings and limitations in a policy context.

The information and analysis in this report are informed by a literature review and interviews. Further details on the methodology, including limitations and caveats, can be found in Appendix A.

1.1. Ammonia pollution in the UK

Ammonia (NH_3) is a colourless gas which is both naturally occurring and manufactured. The main source of ammonia pollution is agriculture, where it is released from manure and slurry and through the application of manmade fertiliser. 82 per cent of all ammonia emissions in the UK in 2016 were from agricultural sources.[1] Ammonia is also emitted in smaller quantities from a range of other sources, including landfill sites, sewage works, car emissions and industry.

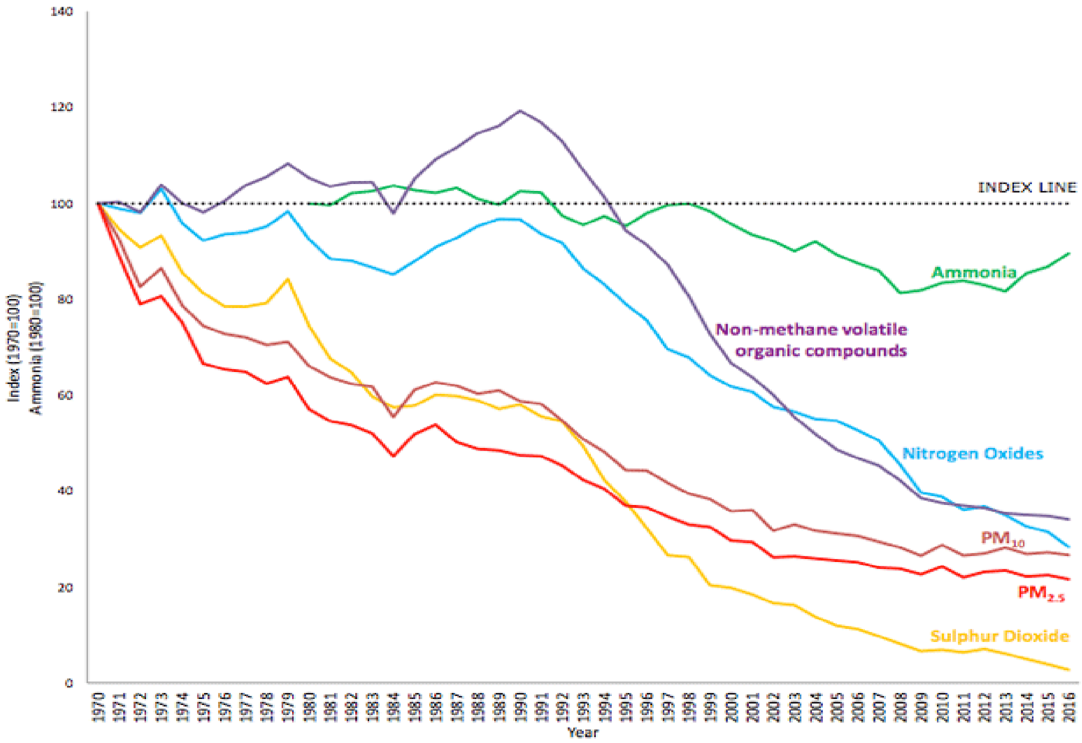
Data shows that emissions of many atmospheric pollutants in the UK have fallen since 1980; however, the same trend has not been seen in relation to ammonia (see Figure 2). Prior to the mid-2000s, ammonia emissions in the UK decreased due to a reduction in pig numbers, reduced use of nitrogen fertilisers

1 NAEI (2016).

and the banning of crop residue burning. The flatlining and small increases in ammonia emissions in the UK since the mid-2000s is due to a reversal of the trend in fertiliser use, increased slurry spreading and an increase in emissions from dairy cattle.[2]

There are several agreed international targets to reduce ammonia emissions and their harmful effects. However, commitments are not as strong as those related to sulphur dioxide and nitrous oxide. Commitments on ammonia include the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) Gothenburg Protocol[3] and the EU National Emission Ceilings Directive (NECD 2016/2284).[4] The Gothenburg Protocol aims to reduce acidification, eutrophication and the harmful effects of ammonia and other pollutants. The emission target for ammonia in EU-28 countries is a reduction of 6 per cent by 2020. The NECD also commits to a reduction of 6 per cent but by 2029. Note that these more general commitments are complemented by stricter emissions targets for sensitive habitats – critical loads and levels for ammonia have been adopted as part of the revised Gothenburg Protocol and are described in Box 2.

Figure 2. Trends in UK sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds, ammonia and particulate matter (PM_{10} and $PM_{2.5}$) emissions 1970–2016



Source: Defra National Statistics Release: Emissions of air pollutants in the UK, 1970 to 2016

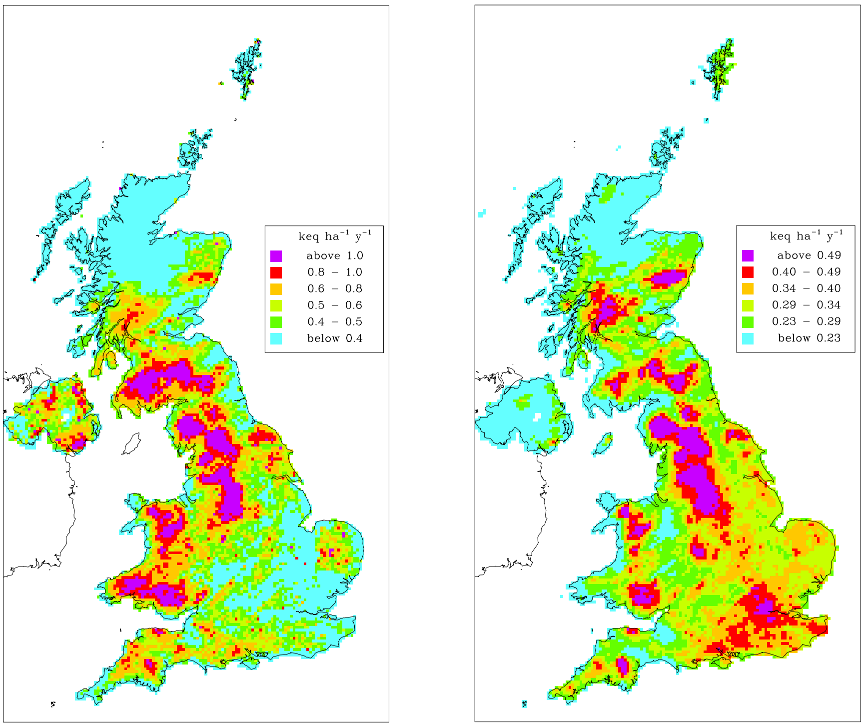
2 NAEI (2016).

3 UNECE (2012).

4 The European Parliament and the Council of the European Union (2016).

When atmospheric ammonia is emitted from agricultural sources, it can either be deposited directly onto vegetation and landscapes (this is termed dry deposition) or transported within the atmosphere and later deposited through rain or snow (wet deposition). At locations very near to the point source of ammonia emissions, the predominant form is dry deposition, while wet deposition is the predominant form in locations further from the source. Patterns of deposition in the UK are shown in Figure 3.

Figure 3. Maps of nitrogen deposition in the UK



(a) **(b)**

Part (a) The annual deposition of reduced nitrogen in the UK averaged over 2014-2016. The map comprises wet deposition of NH_4 and dry deposition of gaseous NH_3.

Part (b) The annual total deposition of oxidized nitrogen in the UK averaged over 2014-2016 The map comprises wet deposition of NO_3 and dry deposition of NO_2 and HNO_3.

Source: R.I Smith et al. (2018)

1.2. Negative effects of ammonia

Ammonia is a pollutant which can have significant effects on both human health and the natural environment. The impacts of ammonia on biodiversity can be a direct toxic effect on vegetation or changes in species composition due to nitrogen deposition, which can result in the loss of sensitive and rare species and habitats (see Chapter 2). Ammonia is only one source of excess nitrogen, alongside nitrogen oxides, NO and NO_2, collectively known as NO_x. NO_x pollution occurs primarily through emissions from transport and industry. The different forms of nitrogen are summarised in Table 2.

Table 2. Different forms of nitrogen[5]

Form of nitrogen	Description
Di-nitrogen (N_2)	A gas which comprises 78% of our atmosphere. Unreactive.
Nitrate (NO_3) and nitrite (NO_2^-)	These ions are oxidised compounds of nitrogen. They are either produced from the oxidisation of ammonia by bacteria in the soil (in a process called nitrification) or supplied directly by manmade fertilisers. Nitrate is commonly found in soils and is the main form that is taken up by plants.
Ammonia (NH_3) and ammonium (NH_4)	Ammonium is the reduced form of ammonia. Both are found in water, soil and air as a liquid or gas. Ammonia is released when organic matter is broken down. It can also be released during combustion, and is synthesised for manmade fertilisers. Ammonium (ionised ammonia) is the form transported in the atmosphere and used by plants as a source of nitrogen.
Nitrogen oxides (NOx)	This includes nitrogen oxide (NO) and nitrogen dioxide (NO_2), gases which are produced naturally by soil bacteria but also by combustion of fuels. As well as depositing nitrogen into the environment, they also cause global warming and acid rain.
Nitrous oxide (N_2O)	A gas released in the breakdown of organic matter and nitrogen fertilisers which has significant implications for global warming.

In the atmosphere ammonia can bind to other gases, such as sulphur dioxide (SO_2) and nitrogen dioxide (NO_x), to form ammonium-containing fine particulate matter (PM). This fine PM causes health impacts when inhaled. Particulate matter has particularly negative impacts on cardiovascular and respiratory health, contributing to various chronic conditions such as heart attacks, cerebrovascular disease, chronic obstructive pulmonary disease (COPD), asthma and lung cancer.[6,7,8,9,10]

Looking forward, regulating emissions in the transport sector such as sulphur dioxide and nitrogen oxide (e.g. reducing use of diesel cars) will result in less ammonia being deposited in cities. This will likely result in a greater proportion of ammonia emissions being deposited on rural landscapes. If we therefore assume that a similar amount of ammonia is emitted from agricultural sources, it is likely that, over time, the impact of ammonia on biodiversity will increase as the human health impacts decline.

5 R. Lillywhite and C. Rahn (2005).
6 Y.Q. Han and T. Zhu (2015).
7 World Health Organisation (2013).
8 Y.F. Xing et al. (2016).
9 I. Kloog et al. (2015).
10 Air Quality Expert Group (2012).

2 Impacts on biodiversity

2.1. What do we mean by biodiversity?

Biodiversity refers to the biological variety of all life on earth or within certain habitats.[11] An ecosystem refers to the interaction of organisms within certain habitats.[12] This review focuses on the impact of ammonia emissions on biodiversity, recognising that biodiversity is a vital component of healthy and functioning ecosystems. Box 1 outlines the common measures of biodiversity.

2.2. Why is biodiversity important?

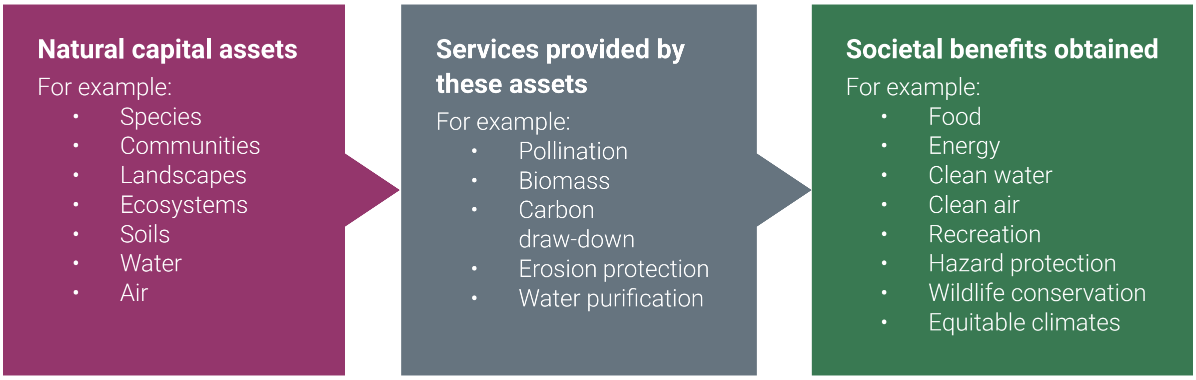
Biodiversity has both extrinsic and intrinsic value. The economic value of ecosystems and biodiversity can be measured through the ecosystem services that these species provide and contribute to. The global value of ecosystem services[14] has been estimated at US$125–145 trillion per year,[15] though this figure is debated. The Natural Capital Committee

Box 1. Measures of biodiversity

Species composition, species richness and species diversity are all measures of biodiversity and indicators of ecosystem function. Species richness refers to the total number of species in a given area,[14] whereas species diversity also considers relative abundance and the evenness with which these species are spread. High diversity means there is a balance of different species within a habitat, while low diversity means there are just one or two dominant species and a few very rare others. Species composition refers to the proportion of different plant species in a given area. Wherever possible we have chosen publications that refer to species diversity or species composition, but much of the literature reports species richness. The difference between these measures of biodiversity should be borne in mind when interpreting the results.

11 Oxford English Dictionary.
12 Oxford English Dictionary.
13 R. Hassan et al. (2015).
14 UK National Ecosystem Assessment (2018).
15 R. Costanza et al. (2014).

Figure 4. Natural capital approaches



Source: Natural Capital Committee (2017b).

defines natural capital as ‘those elements of the natural environment which provide valuable goods and services to people, such as the stock of forests, water, land, minerals and oceans’.[16] Natural capital is comprised of individual assets, such as ecological communities, species, soils, land, freshwaters, minerals, sub-soil resources, oceans, the atmosphere, and the natural processes that underpin their functioning. The pathways linking these to human benefit can be complex (see Figure 4).[17]

The United Nations Environment Programme, the United Nations Convention on Biological Diversity and the World Health Organization have recognised the fundamental role of biodiversity in human health and wellbeing. They summarise the range of benefits as follows:

> *‘Biodiversity, ecosystems and the essential services that they deliver are central pillars for all life on the planet, including human life. They are sources of food and essential nutrients, medicines and medicinal compounds, fuel, energy, livelihoods and cultural and spiritual enrichment. They also contribute to the provision of clean water and air, and perform critical functions that range from the regulation of pests and disease to that of climate change and natural disasters. Each of these functions has direct and indirect consequences for our health and well-being, and each an important component of the epidemiological puzzle that confront our efforts to stem the tide of infectious and noncommunicable diseases’.*[18]

The Natural Capital Committee also recognises that not all natural resources can be assigned a monetary value and has previously noted that changes in biodiversity are particularly hard to value.[19] The United Nations explicitly recognises the intrinsic value of biodiversity, and at the Rio+20 Conference in 2012 member states reaffirmed the ‘intrinsic value of biological diversity, as well as the ecological, genetic,

16 Natural Capital Committee (2017a).
17 Natural Capital Committee (2017b).
18 Convention on Biological Diversity and World Health Organisation (2015).
19 Natural Capital Committee (2017b).

social, economic, scientific, educational, cultural, recreational and aesthetic values'.[20]

2.3. Ammonia in the context of other issues affecting biodiversity

Pollution is recognised by the United Nations as a major threat to global biodiversity,[21] alongside habitat degradation, invasive species and climate change. Target 8 of the Aichi Biodiversity Targets, agreed by all parties to the Convention of Biological Diversity, including the UK, states: 'By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity'.[22]

In most cases, it is a combination of factors and the interaction between factors which reduces biodiversity. For example, ammonia toxicity can make plants more susceptible to pests and diseases. Figure 5 summarises the range of threats to biodiversity and their interactions.

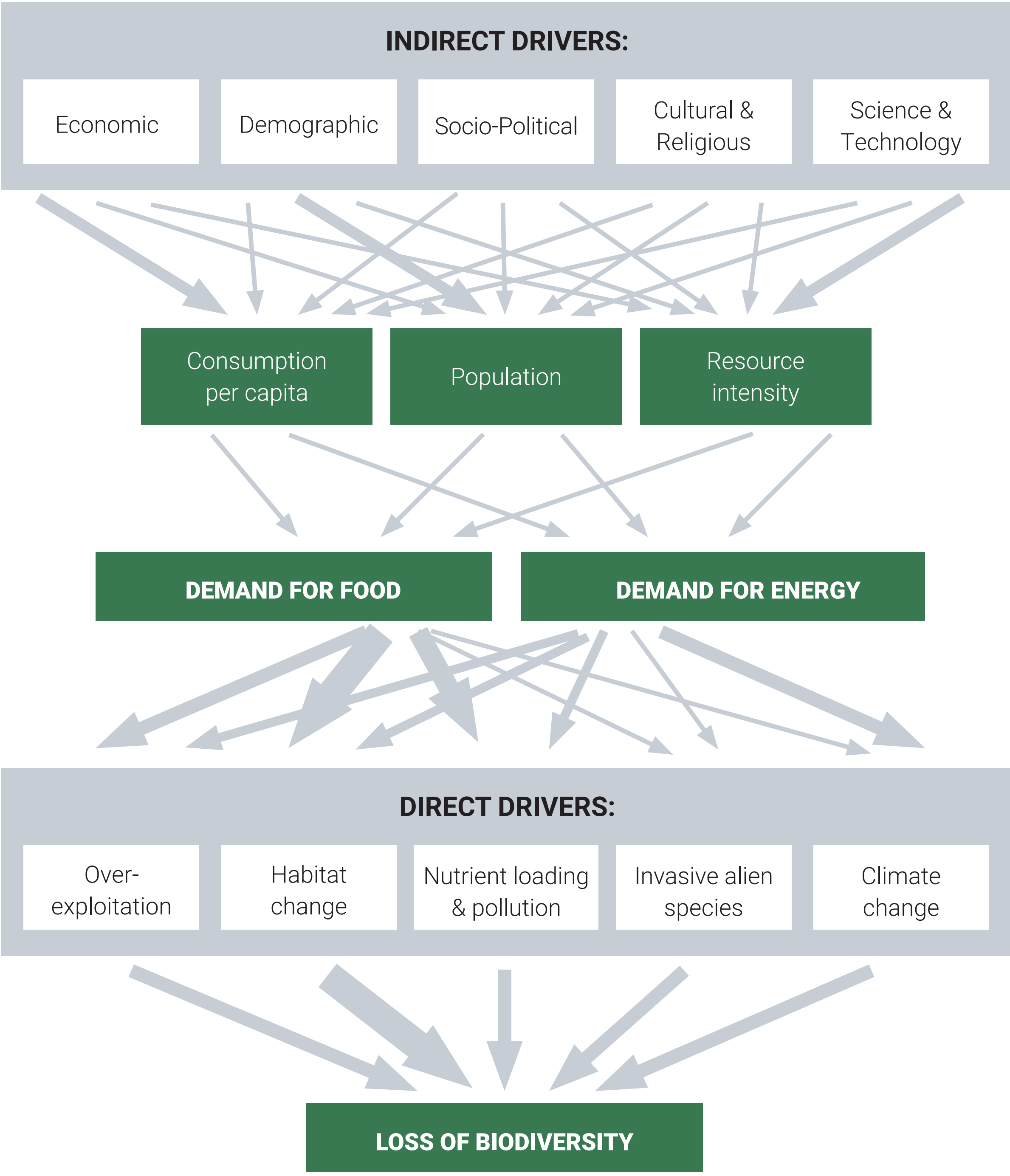
In the context of agriculture, ammonia pollution is just one of a range of impacts on ecosystems. In the UK, 72 per cent of land is managed for food production,[23] and as farming intensifies, changes in land use mean that habitat for wildlife is lost. Change in land use driven by agriculture is one of the biggest threats to global biodiversity. This is compounded by the additional impacts of pollutants. For example, in recent assessments, mosses have been identified as one of the groups of species most under threat in Europe,[24] with 50 per cent of all mosses and liverworts threatened. Mosses and lichens are among the most sensitive species to ammonia pollution.[25]

2.4. Effects of ammonia on biodiversity

A major impact of ammonia pollution on biodiversity is the effect of nitrogen accumulation on species diversity and composition within affected habitats. Common, fast-growing species adapted to high nutrient availability thrive in a nitrogen-rich environment and out-compete species which are more sensitive, smaller or rarer.[26,27,28,29,30,31] This effect is well documented and many authors have observed a decrease in species

20 United Nations Department of Economic and Social Affairs (n.d.).
21 Secretariat of the Convention on Biological Diversity (2014).
22 Convention on Biological Diversity (n.d.-a).
23 Defra (2017).
24 M. Fischer et al. (2018).
25 Air Pollution Information System (2016).
26 C.J. Stevens et al. (2004).
27 R. Bobbink et al. (2003).
28 R. Bobbink et al. (2010).
29 K.N. Suding et al. (2005).
30 Y. Hautier et al. (2009).
31 E.T. Borer et al. (2014).

Figure 5. Links between food, energy and biodiversity loss



Schematic representation of the links between biodiversity loss, the direct and indirect drivers of change, and the demand for food and energy. The width of the arrows gives a broad and approximate illustration of the importance of the economic sectors in driving biodiversity loss.

Source: Convention on Biological Diversity (n.d.-b).

Table 3. Four main mechanisms by which ammonia impacts biodiversity

Mechanism	Description	Pathway
Eutrophication	Accumulation of nutrients in the ecosystem (predominantly nitrogen)	Soil and water
Acidification	Acidification of soil and water due to the deposition of nitrogen compounds	Soil and water
Direct toxicity	Direct damage from ammonia to plant leaves and surfaces	Air
Indirect effects	Predominantly changes in species composition due to a higher nitrogen environment, but ammonia can also alter the susceptibility of plants to frost, drought and pathogens (including insect pests and invasive species)	Air, soil and water

richness[32,33,34,35,36] and species diversity[37,38] in ecosystems with moderate to high ammonia pollution.

The impacts of ammonia on biodiversity occur through four main mechanisms: eutrophication, acidification, direct toxicity and indirect effects.[39,40,41,42] These are described in Table 3 above.

Due to its effect on species composition, ammonia also causes deleterious changes to ecosystem function.[43] At its most serious, if rates of change in species composition and extinction are high, it may be that remaining vegetation and other species no longer fit the criteria for that habitat type, and certain sensitive and iconic habitats may be lost.[44,45,46] Ammonia emissions can also affect animal and insect species indirectly through wider changes to plant species composition, soil and water acidification, and cumulative toxicity. A summary of impacts on insects and other animal species is presented on p.14.

Excess ammonia and nitrogen deposition causes the ratio of carbon to nitrogen in the topsoil to decrease. This can result in excess nitrogen leaching into groundwater, which

32 Air Pollution Information System (2016).
33 C.J. Stevens et al. (2010).
34 R.J. Payne et al. (2013).
35 C.D. Field et al. (2014).
36 L.C. Maskell et al. (2010).
37 L.J. Sheppard et al. (2011).
38 T. Barker et al. (2008).
39 C.J. Stevens et al. (2004).
40 C.J. Stevens et al. (2004).
41 E.T. Borer et al. (2014).
42 S.V. Krupa (2003).
43 C.J. Stevens et al. (2006).
44 R. Bobbink et al. (2012).
45 N.A.C. Smits (2012).
46 G.W. Heil and W.H. Diemont (1983).

leads to the eutrophication of freshwater and also contributes to soil acidification.[47,48] Soil acidification occurs from the atmospheric deposition of nitrogen compounds. All soil has some resilience to and can deal with a certain amount of additional acidity before the pH drops. However, over time, the balance of different elements (including calcium, potassium and magnesium, as well as nitrogen itself) will change in response to acidity. This reduces the ability of the soils to deal with acidification and eventually the pH will fall.[49] Soils are a complex system consisting of water, minerals, organic matter, micro-organisms and soil fauna, and healthy soils are essential for the functioning of the wider ecosystem. The relative balance of nitrogen and other elements can affect the soil as well as the growth and development of plants.[50]

Box 2. Critical loads and levels

Critical loads are defined as 'a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge'.[51] Critical levels are defined as 'concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as human beings, plants, ecosystems or materials, may occur according to present knowledge'.[52] Both are measures which are used to understand what levels of different pollutants are known to cause significant harm. The concept of critical loads and levels has been helpful for policymakers aiming to regulate ammonia pollution.

The critical level for ammonia was originally established in 1992 by the United Nations Economic Commission for Europe at an annual mean of 8μg m^{-3} (micrograms per cubic metre). However, evidence has since shown that exceedance of the critical level can occur at ammonia concentrations far lower than 8μg m^{-3}.[53,54,55] New evidence was twofold. Firstly, the critical level was taken to represent a direct toxic effect of ammonia on ecosystems; however, much of the impact is actually through changes in the competitive ability of plant groups and resulting changes in species composition.[56] Secondly, direct effects of ammonia on lichens in particular are now known to occur at very low ammonia concentrations.[57,58,59] Based on this evidence, the critical levels were revised by UNECE. New critical levels for ammonia are now 3μg m^{-3} and 1μg m^{-3} for lichens and bryophytes respectively.[60]

47 T. Barker et al. (2008).
48 P.M. Vitousek et al. (1997).
49 M. Holland et al. (2018).
50 S.V. Krupa (2003).
51 UNECE website – accessed August 2018.
52 UNECE website – accessed August 2018.
53 M.A. Sutton et al. (2009).
54 J. Burkhardt et al. (1998).
55 J.N. Cape et al. (2009).
56 M.A. Sutton et al. (2009).
57 P. Wolseley et al. (2004).
58 P. Wolseley et al. (2004).
59 J.N. Cape et al. (2009).
60 G. Mills (2017).

2.5. Case studies

The case studies presented demonstrate some of the more specific effects of ammonia on individual species and ecosystems.

CASE STUDY 1: Whim Bog – long-term field studies of the impact of ammonia on a particularly susceptible species/habitat

Whim Bog is a blanket bog located in the Scottish borders. It is a unique experimental site for long-term field studies of the impact of different types of nitrogen pollution, including ammonia, on peatland ecosystems (see Figure 6).

Peatland bogs and heathland are adapted to low nitrogen availability, and experiments at Whim Bog have highlighted the susceptibility of peatland and heathland ecosystems to damage from local dry deposition of ammonia.[61] Gaseous ammonia is alkaline and highly reactive, with a short atmospheric residence time,[62] and a significant fraction being dry deposited within 5km of its source.[63,64] Sheppard et al. (2011) reported that within three years, exposure to relatively modest deposition of ammonia led to dramatic reductions in species cover, with almost total loss of heather, bog mosses and lichen – effects which highlight the potential for local dry-deposition of ammonia to almost completely destroy acid

Figure 6. The Whim Bog experimental site

Source: Matt Jones, CEH.[68]

heathland and peat bog ecosystems. These effects appear to result from direct uptake into the plant rather than via the soil.[65] Similar impacts of ammonia have been observed at Moninea Bog in Northern Ireland (see p.16),[66] following a period of intensive poultry farming near the site.

CASE STUDY 2: Lichens

Many lichens are particularly susceptible to ammonia deposition.[68,69,70,71] Van Herk suggested that lichens may be classified

61 J.N. Cape et al. (2008).
62 U. Dragosits et al. (2008).
63 D. Fowler et al. (1998).
64 M.A. Sutton et al. (1998).
65 L.J. Sheppard et al. (2011).
66 M.A. Sutton et al. (2011).
67 CEH website – accessed August 2018.
68 L. Jones et al. (2013).
69 L.J. Sheppard et al. (2008).
70 L.J. Sheppard et al. (2009).
71 P. Wolseley et al. (2006).

Figure 7. Old Man's Beard (left) and Yellow Rosette Lichen (right)

into species favouring nitrogen-poor (acidic) and nitrogen-rich (alkaline) environments.[72] The relative balance of these different types of lichen is directly proportional to atmospheric ammonia concentrations. In the UK, sensitive lichen species such as Old Man's Beard (see Figure 7, left) are quickly lost from locations with even modest ammonia concentrations,[73,74,75,76] and nitrogen-loving species such as Yellow Rosette Lichen (see Figure 7, right) increase at their expense.[77] Lichens are also present in peatland and heathland ecosystems, and experiments here suggest these species of lichen are similarly sensitive to ammonia pollution.

CASE STUDY 3: Woodlands

Woodlands are impacted by ammonia in a number of ways. Trees themselves may initially have an increased growth rate due to ammonia pollution, via increased nitrogen in the soil. However, in the longer term the soil becomes nitrogen-saturated, resulting in nutrient imbalances and acidification, and ammonia pollution then becomes damaging to growth and development.[78] Ammonia can also significantly alter the diversity and composition of woodland ground flora and other vegetation.[79,80,81,82]

Transitions in the landscape, such as from low vegetation (e.g. grassland or heathland) to woodland, greatly affect the dry deposition of

Figure 8. Woodland in the United Kingdom

72 C.M. van Herk (1999).
73 P. Wolseley et al. (2004).
74 P. Wolseley et al. (2006).
75 J.N. Cape et al. (2009).
76 M.A. Sutton et al. (2011).
77 M.A. Sutton et al. (2009).
78 S.V. Krupa (2003).
79 C.E.R. Pitcairn et al. (1998).
80 C.E.R. Pitcairn et al. (2002).
81 C.E.R. Pitcairn et al. (2003).
82 C.E.R. Pitcairn et al. (2005).

air pollutants such as ammonia.[83,84,85] The dry deposition of ammonia and other pollutants at a woodland edge is significantly higher than that in the centre.[86,87] In small, fragmented woodlands, such as those in the UK, a higher proportion of all vegetation may be strongly affected by ammonia pollution due to all vegetation being nearer the edge.[88]

Concentrations of atmospheric ammonia decline exponentially with distance from many livestock farms, and the species diversity of woodland ground flora decreases the closer the woodland is to farm sites which are large emitters of ammonia.[89,90,91,92] Significant reductions in species diversity were found to occur in woodland within 50m of livestock buildings at a site in Scotland.[93]

CASE STUDY 4: Grasslands

Many semi-natural grassland ecosystems are dominated by species with low nutrient requirements and are therefore sensitive to acidification, eutrophication or both.[94] Acid grasslands have been extensively studied with respect to ammonia and nitrogen deposition. Dupré et al. (2009) found that across Europe, a decline in species richness in acidic grasslands is due to cumulative nitrogen deposition as well as soil pH and other climatic factors.[95] Stevens et al. (2010) found evidence that soil acidification, caused in part by nitrogen deposition (as well as sulphur deposition), is the major contributor to shifts in species composition in acid grasslands, where there was an observed increase in more acid-tolerant grasses and decrease in overall species richness.[96] Data from van den Berg et al. (2016) support this and also demonstrate that nitrogen pollution alone affects species richness, even after accounting for the effects of historic sulphur pollution.[97]

Calcareous (or alkaline) and other grasslands are also negatively affected by nitrogen deposition. The amount of low-growing herbs, short-lived species, nitrogen-fixing plants, rare species and lichens will decrease. Conversely, nitrogen-loving species, which are often fast-growing, large grasses, will dominate (see Figure 9).[98,99,100]

83 C.E.R. Pitcairn et al. (1998).
84 K. Wuyts et al. (2008).
85 U. Dragosits et al. (2002).
86 G.P.J. Draaijers et al. (1988).
87 G.P.J. Draaijers et al. (1994).
88 R. Bobbink et al. (2012).
89 C.E.R. Pitcairn et al. (1998).
90 C.E.R. Pitcairn et al. (2002).
91 C.E.R. Pitciarn et al. (2003).
92 C.E.R. Pitciarn et al. (2005).
93 C.E.R. Pitcairn et al. (2009).
94 N.B. Dise et al. (2011).
95 C. Duprè et al. (2009).
96 C.J. Stevens et al. (2010).
97 L.J.L. van den Berg et al. (2016).
98 R. Bobbink et al. (1998).
99 C.M. Clark et al. (2007).
100 C.J. Stevens et al. (2010).

Figure 9. Calcareous grassland vegetation without excess nitrogen (left) and after 3 years treatment with 100kg N ha^{-1} yr^{-1} (right) showing dominance of nitrogen-loving species and reduced diversity[101]

Source: R. Bobbink (1991).

CASE STUDY 5: Animals and whole ecosystems

Firstly, it must be noted that there is very limited evidence on the effects of ammonia on animals and wider ecosystem function. Presented here are some of the limited examples which do exist.

We can infer that changes in the composition of vegetation due to ammonia will affect animal species; however, these effects are mostly indirect. Animals depend on vegetation as a habitat and as a food source. The only direct effects of ammonia on animal species are observed in the aquatic environment, primarily from point source run-off of effluent from farmlands. Eutrophication due to excess nitrogen in the water causes algal blooms, changes in species composition and a depletion of oxygen within a freshwater system.[102] This can lead to a loss of key species and a loss of the services that these ecosystems provide.[103,104,105] Nitrogen can also be directly toxic to animals in aquatic ecosystems.[106] Aquatic animals often have thin and permeable skin surfaces and gills for oxygen uptake, which come into direct contact with the polluted environment.

For insects and small animal species, changes in vegetation can cause changes to the microclimate near to the surface of the soil. Greater availability of nitrogen in the soil results in greater production of plant biomass, and a thicker and denser layer of vegetation and leaf litter. There is therefore less sunlight, a lower temperature and less airflow on the soil surface. This leads to a cooler and damper environment for invertebrate species and therefore slower development and a longer lifecycle. For larger insect species, which already have a relatively long lifecycle, there is a risk that their lifecycle will not be completed in one season and the species

101 Note this is a high load of nitrogen, greater than is found in UK sites typically.
102 G. Maier et al. (2009).
103 S.R. Carpenter et al. (1998).
104 V.H. Smith et al. (1999).
105 V.H. Smith et al. (2006).
106 J.A. Camargo & Alonso (2006).

may be lost (for example locusts).[107,108] In grassland ecosystems this leads to the disappearance of larger species in favour of smaller species.[109] Insect species preferring drier, brighter environments may also be out-competed by those preferring colder, moister environments, as has been observed in ground beetles.[110]

Many animal species also depend on plants as a food source; therefore, changes in the quantity and quality of vegetation food sources may make herbivorous animals susceptible to the negative effects of ammonia pollution. Flower-visiting insects depend on flowering plants for their energy and nutrients, and wild flowers become less common in a nitrogen-rich environment. More nitrogen pollution is associated with fewer butterfly and moth species[111,112,113,114] and changes in species composition (with an increase in butterflies whose larval caterpillars are adapted to nitrogen-rich environments).[115] Bee populations are also very sensitive to changes in plant species composition.[116,117,118]

Changes in microclimate and food supply may mean that as well as a loss of some species, other species better adapted to a nitrogen-rich environment may increase, sometimes to the detriment of the wider ecosystem. For example, increases in the frequency of heather beetle outbreaks have also been attributed to a higher-nitrogen environment due to ammonia deposition from intensive farming.[119,120,121]. Outbreaks of these beetles cause the defoliation and death of heather plants and, as a result, heathland ecosystems have been replaced by grasslands in some parts of the Netherlands.[122]

The effects of nitrogen deposition on vegetation and subsequently on insect species can cascade further through the food web. As presented by Dise et al. (2011), the decline in the red-backed shrike is a good European example (see Figure 10). Much of the loss of this species is correctly attributed to habitat loss; however, in coastal dunes in Germany, Denmark and the Netherlands, habitat loss has not occurred and the pattern in population loss can be attributed to

Figure 10. The red-backed shrike, a species that has been indirectly impacted by chronically elevated nitrogen deposition

Source: E. Dirksen from N.B. Dise et al. (2011).

107 W.K.R.E. van Windergerden et al. (1991).
108 W.K.R.E. van Windergerden et al. (1992).
109 R. Bobbink et al. (2012).
110 M. Nijssen et al. (2001).
111 S.B. Weiss (1999).
112 R. Bobbink et al. (2012).
113 A.P. Fowles & R.G. Smith (2006).
114 A. Salz & T. Fartmann (2009).
115 E. Ockinger et al. (2006).
116 D. Goulson et al. (2002).
117 J.C. Biesmeijer et al. (2006).
118 J. Frund et al. (2010).
119 N.R. Webb (1989).
120 S.A. Power (1998).
121 S.V. Krupa (2013).
122 A.M.H. Brunsting (1982).

nitrogen deposition.[123] Red-backed shrikes require a high diversity of insect and small lizard prey species, and nitrogen deposition makes the grasslands more homogenous and dominated by taller, thicker grasses, within which larger insect prey cannot survive. This availability of large prey species has been identified as the main factor contributing to the decline of the red-backed shrike in these regions.[124]

CASE STUDY 6: Moninea Bog – gradient effect of point source ammonia emissions on a European Special Area of Conservation

Moninea Bog is a lowland raised bog in Northern Ireland and a designated European Special Area of Conservation.[125] The habitat contains many bog moss species native to the British Isles, some of which are rare. An intensive poultry farm had begun operations to the northwest of the site and based on concerns, concentrations of atmospheric ammonia across the site were measured in 2007. The results showed that the moss species at the site were under substantial threat from atmospheric ammonia emissions and that there was a clear gradient effect, with effects strongest near the poultry farm site.[126] The most dramatic effects were visible injury to lichen and bog moss species, which are essential for the peat-building function of such sites. Two examples of this damage are shown in Figure 11. Initially high ammonia concentrations result in algal growth over the surface of the bog moss plant. This gradually smothers and kills the moss by limiting gas exchange and photosynthesis.

Figure 11. Photographs illustrating the impact of ammonia pollution from a poultry farm on lichen and bog moss at Moninea Bog, a Special Area of Conservation in Northern Ireland

Source: M.A. Sutton et al. (2011).

Between 2004 and 2007 there was a 50 per cent loss of bog moss in locations less than 400m from the poultry farm, and it was estimated that up to 200m downwind of the farm, lichens and mosses were more than 90 per cent eradicated or injured. Moninea Bog is a unique case study which allows a strong link to be established from source attribution, through nitrogen accumulation, to eventual loss of key species and ecosystem integrity.[127]

123 P. Beusink et al. (2003).
124 H. Esselink et al. (2007).
125 Joint Nature Conservation Committee (2017).
126 M.A. Sutton et al. (2011).
127 M.A. Sutton et al. (2011).

2.6. Quantifying costs of biodiversity loss

Quantifying the impact of ammonia emissions on biodiversity in terms of their equivalent costs is challenging. Various methods have been used and there is no clear consensus on the best way to estimate the costs associated with biodiversity loss. A commonly used approach is 'willingness to pay', where numerical estimates are made of the value that members of the public place on maintaining biodiversity.[128] There remains variation between these estimates due to the approach taken – for example, the types of habitats covered, or the nature of the species included. Other estimates use restoration costs, which are the costs that would be required to restore ecosystems damaged by ammonia; or regulatory-based approaches, which are based on the air pollution abatement costs implicit in legislation. There are also some wider estimates of the ecosystem impacts of nitrogen, to which ammonia makes a significant contribution but is not the sole source. Table 4 summarises the range of values associated with biodiversity loss due to ammonia emissions based on different methods employed in key recent studies. Notably, many studies only cover specific habitats (e.g. terrestrial or freshwater). Taking this into account, we conservatively estimate that for the UK the costs are likely to be in the range £0.2–£4 per kg of ammonia (higher estimates by Brink et al. (2011) are not included since these are not UK-specific).

In addition, ammonia emissions have significant health impacts, and the costs of these have been estimated to be in the range £2 to £52 per kg of ammonia (see Table 5).[129]

128 This can be estimated by a number of methods, all of which rely on hypothetical scenarios, so that stated preferences rather than observed behaviour is used. In one approach, respondents may be directly asked the maximum they would be willing to pay for retaining or maintaining biodiversity. Alternatively, respondents are asked to choose between different sets of options that cover the main characteristics of biodiversity, including cost. The characteristics are described by a few different levels (values). Willingness-to-pay for biodiversity (and its main characteristics) can then be calculated from the reported choices using a model.

129 Figures are based on estimating life years lost and placing a fixed value on these. Range of values comes from differences in range of health impacts covered, the estimate of the level of mortality from each of these, and different valuation of the lost years of life.

Table 4. Estimated values of the cost of biodiversity loss due to ammonia emissions

Method used	Estimate (£ per kg of NH_3, 2018 prices)[130]	Caveats	Source(s)
Willingness to pay	£0.42[131]	Includes breakdown by habitat type and notes differential dose response depending on existing nitrogen deposition. UK-specific.	Jones et al. (2018)
Ecosystem restoration	£0.24 for UK[132]	Assumes society willing to bear the costs of restoration and provide a lower bound estimate of those costs.	Ott et al. (2006)
Ecosystem damage through terrestrial deposition – review and analysis of prior estimates[133]	£3.40–£16.80[134]	For all of Europe, not UK-specific. Based on estimates for nitrogen rather than ammonia specifically.	Brink et al. (2011)
Environmental costs of freshwater eutrophication, mixed approach	£0.60[135]	No distinction made between effect of nitrogen and phosphorous, and costs are quite heterogeneous. Values extrapolated by Brink et al. (2011) for N only. Freshwater costs only.	Pretty et al., (2003), analysed by Brink et al. (2011)
Stated regulatory preference	£3.70 for UK[136]	Based on comparing current legislation to the costs associated with alternative legislative approaches and the reductions in emissions they would produce.	Eclaire (2015)

Source: RAND Europe analysis.

130 Converted to 2018 prices using Consumer Price Index (CPI), Office of National Statistics (2018).

131 £414 per tonne (2017 prices).

132 €0.12 per kg in the UK (2004 prices).

133 Lower bound based on Ott et al. (2006) representing the cost for restoring biodiversity loss; upper bound arbitrarily set at five times lower bound as a possible value when using an ecosystem service approach.

134 €2–10 per kg N, in 2004 prices.

135 €0.30 per kg N, 2002 prices.

136 Assumed 2014 prices (not stated).

Table 5. Estimated values of the cost to human health of ammonia emissions[137]

Estimate (£ per kg of NH3, 2018 prices)[138]	Notes on methods	Source(s)
£1.91[139]	Estimate based on decreases in mortality and morbidity using the value of life years lost (VOLY) approach where a value is assigned to each year. UK air quality policy currently uses a VOLY value of £29,000 (in 2005 prices) based on Chilton et al. (2004).[140] This study accounts for population demographics over a 100-year time window, starting from the base year of 2005, reflecting the fact that health implications from air pollution typically take a long time to emerge.	Watkiss (2008)
£30[141]	Unit damage costs for health impacts of airborne NH_3 using VOLY value of €40,000 per life year[142] and the CAFE/WHO methodology.[143]	NEEDS Study – Ott et al. (2006)
£23[144]	Value based on the impact of NH_3 inhalation, including direct impacts (negligible), impacts via PM_{10} and odour (small). Effects include asthma, respiratory disorders, inflammation of airways, reduced lung functions, bronchitis, cancers.	Values based on Holland et al. (2005a)
£2.39[145]	Based on a valuation of chronic mortality caused by $PM_{2.5}$.	Values derived by Anthony et al. (2008) based on Spencer et al. (2008)
£23[146]	Chronic mortality, chronic and acute morbidity caused by $PM_{2.5}$, along with effects on crops by hindering tropospheric ozone formation (i.e. not solely health impacts).	Values derived by Anthony et al. (2000) based on Spencer et al. (2008) and Baker et al. (2007)
£20[147]	Chronic mortality, chronic and acute morbidity caused by $PM_{2.5}$, along with effects on crops by hindering tropospheric ozone formation (i.e. not solely health impacts).	Values based on Brink et al. (2011)

137 V. Eory et al. (2013).

138 Converted based on CPI, ONS (2018) and ONS conversion data for sterling to euros.

139 £1,407 would accrue per tonne reduction in NH3 (2005 base year).

140 S. Chilton et al. (2004).

141 UK is €21 per kg NH3 -N (range 0.1–10) based on VOLY of €40,000. NB: converting to £29,000 per VOLY, would be £21 per kg.

142 UK air quality policy currently uses a VOLY value of £29,000 (in 2005 prices) based on Chilton et al. (2004).

143 M. Holland et al. (2005b).

144 €9.50 per kg NH3 (2000 prices).

145 £1,804 per tonne of NH3-N (2006 prices).

146 £17,699 per tonne (2006 prices).

147 £17,699 per tonne based on value of €40,000 per VOLY.

Estimate (£ per kg of NH3, 2018 prices)[138]	Notes on methods	Source(s)
£52[148]	Chronic mortality, chronic and acute morbidity caused by $PM_{2.5}$, along with effects on crops by hindering tropospheric ozone formation (i.e. not solely health impacts).	Values based on Holland et al. (2005a)
£14[149]	Based on unit damage costs damage for airborne NH_3.	Brink et al. (2011) based on ExternE (2005)
£2.33[150]	Value recommended by Defra for UK policy appraisal of human health impacts related to the $PM_{2.5}$ aerosol component of ammonia.	Dickens et al. (2013)

Source: RAND Europe analysis, expanded from Eory (2013, p.58 – Table 1).

Combining an estimate of around £2 per kg for health impacts[151] with an estimate of £0.42 for impacts on biodiversity,[152] we arrive at a conservative estimate of the total costs from both health and biodiversity impacts of £2.50 per kg of NH_3.[153] Combining this with projected emission data,[154] we can provide an indicative estimate of overall cost equivalents to the UK of ammonia emissions. If no action is taken to reduce emissions, the costs are estimated to be over £700m per year. As noted above, there are significant uncertainties in these values. The range of possible costs, based on the estimates in the literature and best available projections for emissions,[155] are between £580m[156] and £16.5bn[157] per year.

It should be noted that the costs to human health and biodiversity only capture some of the impacts of ammonia, which can be positive as well as negative. Taking an ecosystem services approach, Jones et al. (2014) identified and costed other impacts of ammonia, including on timber production, food production, carbon sequestration, nitrous oxide emissions and recreational fishing, alongside appreciation of biodiversity. For food and timber production and carbon sequestration, ammonia emissions are beneficial. This means

148 £52,055 per tonne based on value of €40,000 per VOLY.

149 Inferred social costs of health impacts from secondary ammonium particles. Based on unit damage costs for airborne NH3 (€12 per kg N r) from ExternE (2005) after conversion of results per mass of pollutant to mass of nitrogen in pollutant by Brink et al. (2011). Based on €40,000 per VOLY.

150 £1,972 per tonne (2010 prices).

151 Based on the Watkiss (2008) and Dickens et al. (2013) estimates which are most relevant to the UK context, use the UK standard values for a VOLY and do not include additional costs (e.g. related to crop damage).

152 Based on the most comprehensive and recent analysis in the UK context, by Jones et al. (2018).

153 Close to the Defra figure of £2.79 per kg.

154 A. Misra et al. (2012).

155 Note there is also variation year on year. Projected emissions levels are available for 2020, 2025 and 2030. However, changes between these periods in projected emissions levels per year are small relative to uncertainty in the estimate. Estimates are presented for 2020 data.

156 Based on lowest possible emissions scenarios and costs of £2.15 per kg.

157 Based on highest possible emissions scenario and costs of £56 per kg.

that reductions in ammonia emissions have a negative impact on these services, reducing the overall estimate of the benefits accrued. Jones et al. also note that many of the benefits from ammonia reductions for ecosystem services are hard to quantify. Given this, as well as the significant variation in the estimates of the costs both to human health and biodiversity, the estimates provided here should be treated as indicative of the scale of the problem rather than absolute.

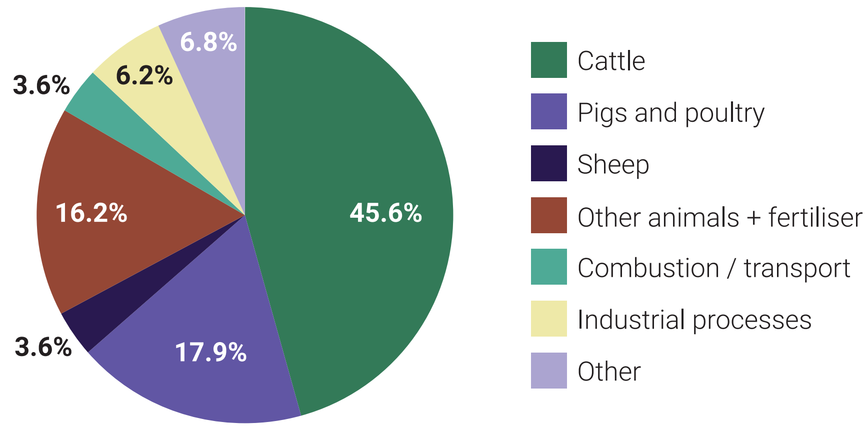
3 Methods for reducing ammonia emissions from agriculture

There are a number of interventions that can be used to reduce ammonia emissions from agriculture. In this chapter we explore the range, effectiveness, costs and acceptability of a number of key options, covering:

- Livestock feed
- Animal housing
- Manure spreading
- Manure storage
- Non-organic fertiliser
- Other methods.

These areas represent the main sources of ammonia emissions within farming. Most ammonia emissions are from livestock production, with the largest segment of that due to cattle, particularly dairy farming. Nearly half of emissions are from manure spreading, followed by a third due to animal housing, and the remainder from waste storage and grazing.[158] We discuss interventions in a broad context, but focus on those most relevant to the UK, noting the make-up of the UK agricultural sector and the key sources of ammonia emissions as set out in Figure 12.

Figure 12. UK ammonia emission sources in 2014



Source: Y.S. Tang et al. (2018).

158 National Atmospheric Emissions Authority (2016).

3.1. Livestock feed

Most (66–85 per cent) of the nitrogen consumed by farm animals is excreted in faeces and urine.[159] Excess protein ingested by animals is excreted as nitrogen compounds, leading to ammonia emissions. Therefore, limiting the excess protein which animals are fed can reduce ammonia emissions at source. This can be done by maximising the fraction of protein that animals metabolise and minimising the fraction of protein they cannot metabolise. There are a number of ways to do this, such as ensuring that levels of crude protein do not exceed the recommended amounts for nutritional needs. These levels will vary with the profile of the animal. For example, the nutrient requirement drops as the animal's age and weight increase.[160]

For cows and sheep, the level of excretion depends on the ratio of grass, grass silage, hay and grain the animals consume. Measures to reduce protein surplus in feed include substituting fresh grass with lower-protein feed such as mature grass or straw, as well as minimising N-fertiliser application rates on grass and maintaining the quality of crude protein when making silage for winter feeding. The latter can be done by, for example, silaging grass as fast as possible after cutting, amongst other measures. Finally, increasing grazing time helps reduce emissions. This is because the distributed urine can be absorbed into the soil and broken down before ammonia is released.[161] The efficacy and acceptability of these various options are presented in Table 6. Some of these measures (such as reducing levels of nitrogen in animal feed) are already being implemented, though further education is needed.[162] Challenges include higher feed costs for farmers, and the risk of having an imbalanced nutrient level in the farm as the full use of grass produced within the farm is not guaranteed.

Intervening at the point of feeding impacts all stages of manure management and is therefore an important step in reducing ammonia emissions. According to Bittman et al. (2014):

> *'Low-protein animal feeding is one of the most cost-effective and strategic ways of reducing ammonia emissions. For each per cent (absolute value) decrease in protein content of the animal feed, ammonia emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5–15 per cent, depending also on the pH of the urine and dung'.*[163]

159 P. Ferket et al. (2002).

160 P. Ferket et al. (2002).

161 UNECE (2015).

162 Defra (2007).

163 S. Bittman et al. (2014).

Table 6. Percentage reduction of ammonia emissions, cost and likely uptake of interventions in livestock feed

Method	Percentage reduction of ammonia emissions (%)	Cost of implementation (£ per kg of NH_3)[164]	Likely uptake[165]
Decreasing crude protein concentration	30–44 for cattle[166] Up to 62 for pigs[167]	Typically in the range -£2.30–+£2.30 for feed adjustments as a whole	Dairy: low to moderate Pigs: uptake for N would be higher with stronger economic incentives
Phase feeding (adapting food for animal's age, weight, etc.)	10–30[168,169,170]	As above	Dairy: moderate to high Pigs: low without financial incentives
Increased grazing time	Up to 50 (but depends on increased grazing time and baseline)[171]	Not available	Low – limited by suitable soil types and climate

3.2. Animal housing

When livestock are kept indoors, ammonia emissions can be reduced by designing the facilities they are housed in to better contain manure.[172,173] Generally, the motivation behind these strategies is to reduce the surface area that is exposed to livestock urine and manure.[174] The greater the surface area of manure exposed to the air, the greater the ammonia loss. From the initial design stage, useful features that control ammonia emissions include using slatted floors for the manure to fall into manure collection pits.[175,176] These collection pits can also include sloped walls so that the surface area for the slurry is as small as possible. Alternatively, floors can be grooved to allow for urine drainage.[177,178] Particularly for facilities housing pigs, it is

164 Costs all based on Bittman et al. (2014).
165 Defra (n.d.).
166 S.L.M. Preece (n.d.).
167 E.T. Hayes et al. (2003).
168 N.A. Cole and R.W. Todd (n.d.).
169 N.A. Cole et al. (2005).
170 N.A. Cole et al. (2006).
171 S. Bittman et al. (2014).
172 UNECE (2015).
173 It should be noted that this needs to be managed in line with and not at the expense of animal welfare.
174 S. Bittman et al. (2014).
175 UNECE (2015).
176 J. Webb et al. (2006).
177 L. Loyon et al. (2016).
178 UNECE (2015).

possible to use animal behaviour to reduce dung and urine on solid spaces by having separate spaces for different functions (e.g. lying down and dunging). Additionally, ammonia emissions can be reduced by keeping the air temperature and airflow low around areas with manure.[179,180]

There are other interventions related to livestock housing that are not predicated on a new building design, but instead require more active maintenance from farmers. Recommendations to reduce ammonia emissions include separating urine from manure and regular cleaning of areas soiled by manure.[181,182] If animals live on straw indoors, increasing the straw per animal can help keep ammonia emissions down by providing a barrier between the urine and the air, and additional straw supplemented in particularly wet areas.[183,184,185,186] In addition, the use of straw leads to collection of waste as a solid rather than a liquid slurry, which is easier to store and emits less ammonia.[187]

If the facility is ventilated through artificial means, keeping the exhaust air fan clean can also make an impact.[188,189] Acid scrubbers can be employed in artificially ventilated buildings, which capture ammonia from the exhaust air.[190,191] Alternatively, livestock could graze outside the facility for longer periods of time. This would mean that less ammonia would be produced since some of the urine would be absorbed into the ground before releasing ammonia, as well as being recaptured by the vegetation.[192]

There are costs associated with depreciation of investment in housing facilities, energy costs, and costs for operation and maintenance. Costs are variable, and it should be noted in particular that low-emission cattle-housing techniques are relatively nascent and as such costs are subject to change. There can also be benefits from the improved housing in relation to animal health and performance, but these have not often been assessed.[193] Housing modifications are likely to incur upfront costs, implying that it is more cost-effective to include measures when erecting new buildings than to retrofit existing buildings.

There are many options that could be employed in a livestock facility, though they are not all equally effective in reducing ammonia (see Table 7).

179 S. Bittman et al. (2014).
180 P.A. Dumont et al. (2012).
181 S. Bittman et al. (2014).
182 UNECE (2015).
183 S. Bittman et al. (2014).
184 UNECE (2015).
185 Y. Zhang et al. (2017).
186 J.P. Newell Price et al. (2011).
187 J.P. Newell Price et al. (2011).
188 S. Bittman et al. (2014).
189 UNECE (2015).
190 L. Loyon et al. (2016).
191 UNECE (2015).
192 L. Loyon et al. (2016).
193 S. Bittman et al. (2014).

Table 7. Percentage reduction of ammonia emissions by interventions in animal housing

Method	Percentage reduction of ammonia emissions (%)	Cost of implementation (£ per kg of NH_3)[194]	Likely uptake[195]
Air scrubbing techniques	70–90[196,197]	£1.00–£18.00 (depending on animal)	Low: only practically applicable to new build sites
Washing floors and other soiled areas in livestock facilities[198]	40–90[199]	Not available	Low due to extra labour and additional volume of slurry
Increasing the outdoor grazing period for livestock	Up to 50[200,201,202]	Not available	Low: limited by suitable soil types and climate
Floor design including slats, grooves, v-shaped gutters and sloping floors to collect and contain slurry faster	25–65[203,204]	£1.00–£23.00	Low due to high costs of building conversion
Optimal barn acclimatisation with roof insulation and/or automatically controlled natural ventilation	Up to 20[205]	Not available	
Surface cooling of manure	45–75[206]	£7.00–£18.00	
Acidifying slurry and shifting the chemical balance from ammonia to ammonium	50–60[207]	£6.00	
Straw bedding for cattle housing	Up to 50[208]	Not available	Low: less-suited to regions where little straw is produced (e.g. southwest England and Wales)

194 All costs based on Bittman et al. (2014).

195 J.P. Newell Price et al. (2011).

196 L. Loyon et al. (2016).

197 UNECE (2015).

198 This method increases the volume of contaminated water that eventually needs to be treated in a way that does not further spread the source of other pollutants.

199 L. Loyon et al. (2016).

200 L. Loyon et al. (2016).

201 J.P. Newell Price et al. (2011).

202 S. Bittman et al. (2014).

203 L. Loyon et al. (2016).

204 UNECE (2015).

205 UNECE (2015).

206 UNECE (2015).

207 UNECE (2015).

208 J.P. Newell Price et al. (2011).

3.3. Manure storage

Manure is spread on fields as an organic fertiliser to increase crop yield. Up to 90 per cent of nitrogen excreted in manure can be used again, although in reality the rate of reuse achieved is often smaller.[209] It is often stored until required. Storage enables manure to be spread both in optimal conditions and in times of low soil nutrients. Storage vessels include concrete, steel or wooden tanks, earth-banked lagoons, pillows and bags. The surface area of manure exposed to the air during storage influences the ammonia loss. This means that lagoons, which have a high surface area, have particularly high levels of ammonia loss, whereas stores designed with increased height and reduced width are more practical for reducing ammonia emissions.[210] Fully enclosed storage (e.g. covered stores and bags) has the lowest ammonia emissions.

Reducing the airflow across a slurry store's surface decreases ammonia emissions. There is substantial consensus within the literature that ammonia emissions are reduced when the surfaces of slurry stores are covered.[211,212,213,214] Covers can be solid and can include lids, roofs and tent structures, or floating (often plastic) sheets fixed to the store wall. Plastic sheeting can also be used to cover solid manure stores.[215] Cattle slurries and some pig slurries can have a natural crust on the surface dependent on dry matter content, otherwise floating crusts composed of straw, granulates or other materials can be introduced.[216,217,218] The efficacy and the specific limitations of these various options are presented in Table 8.

The likely uptake of covers is rated by Newell Price et al. (2011) as low to moderate. The reasons given for this are cost implications, logistical issues with lagoons and existing tanks with insufficient structural support to add a rigid lid.[219] On the other hand, it is estimated that natural crusts are already used on 80 per cent of slurry stores, and Newell Price et al. therefore estimate the additional likely uptake to be low as this measure is already in place. When slurry stores are covered with either solid covers or certain floating cover types, rainwater is prevented from entering the store. This enables a higher volume of manure to be stored in the tank and makes for easier transportation as the volume is not increased through dilution.[220] Covers may also reduce the release of other greenhouse gasses, such as methane, into the atmosphere.[221,222]

209 O. Oenema et al. (2011).
210 S. Bittman et al. (2014).
211 T.H. Misselbrook et al. (2004).
212 K. Smith et al. (2007).
213 S.G. Sommer et al. (1993).
214 Defra (n.d.).
215 UNECE (2015).
216 T.H. Misselbrook et al. (2004).
217 K. Smith et al. (2007).
218 S.G. Sommer et al. (1993).
219 J.P. Newell Price et al. (2011).
220 S. Bittman et al. (2014).
221 B. Amon et al. (2006).
222 Defra (n.d.).

Table 8. Percentage reduction of ammonia emissions and limitations by interventions in application of different manure storage solutions

Method	Percentage reduction of ammonia emissions (%)[223]	Cost of implementation (£ per kg of NH_3)[224]	Considerations[225]
Solid cover	Tight cover: more than 80	£1.20–£3.00	If impermeable, gasses may build up inside
Floating cover	40–80 Plastic cover: 60	£0.60–£1.50 £0.40–£6.00	Need to prevent cover turning over in wind or when mixing
Natural crust	40–50	Crusts form naturally and therefore have no associated cost	Efficiency depends on nature of crust (optimal crust is thick and covers surface fully) Less predictable and so the emissions reduction can be variable Not suitable when need to mix slurry to spread frequently Only form on certain slurry types
Floating crust	50–60	£0.40–£1.00	Addition of straw (and therefore carbon) can increase nitrous oxide and methane emissions Not suitable when need to mix slurry to spread frequently
Replace lagoons with deep tanks	30–60	Difficult to estimate because depends on characteristics of tank	Makes it difficult to mix slurry
Storage bags	100	£3.00 per m^3/yr, including storage costs	May not be suitable for very large quantities of slurry

3.4. Manure spreading

Manure has been used for centuries to enrich soil with nutrients including nitrogen, often being spread by farmers to increase crop yield. However, ammonia release from manure spreading contributes substantially to the UK's agricultural ammonia emissions.[226] Reducing ammonia release at this step is particularly important, as any ammonia conserved through previous steps, such as animal housing and

223 J.P. Newell Price et al. (2011).

224 Costs all based on Bittman et al. (2014).

225 Data from UNECE (2015) and Bittman et al. (2014).

226 25 per cent of UK agricultural ammonia emissions in 2016 were from manure application. The only category accounting for a higher percentage is livestock housing (27 per cent).

manure storage, could now be released and good work undone.[227,228]

Traditionally, manure is spread using a technique called 'broadcast application'. This technique proves problematic, as manure is exposed to air for prolonged periods, causing high levels of ammonia to be released into the atmosphere. Several techniques can be used to reduce manure–air contact, the simplest being rapid incorporation of the manure into the soil.[229] Other low-emission application methods include band spreading techniques such as trailing hose[230] and trailing shoe.[231] Slurry can also be injected beneath the soil surface, increasing soil infiltration.[232] Spreading methods distribute the slurry more uniformly than broadcast application, and also reduce the amount of slurry deposited onto the plant surface, preventing plant contamination while increasing soil nutrient content.[233]

Making manure more acidic (pH 6 or below) decreases the proportion of volatile ammonia, reducing ammonia release.[234,235,236] Manure can be diluted, either through addition to water irrigation systems or store tanks, to aid soil infiltration and reduce NH_3 loss. Climatic conditions can also affect the amount of ammonia lost. For example, higher wind speeds increase transfer and air exchange, therefore increasing the ammonia loss.[237] Rain moves the ammonium into the soil, and therefore significant rainfall after application reduces ammonia emissions. Whilst specific weather conditions cannot be managed to control ammonia loss, making use of conditions on a seasonal or daily basis has been proposed.[238] Timing manure application to coincide with cool, humid and windless conditions can reduce both NH_3 release and its spread to sensitive ecosystems.[239,240]

Overall, the likely uptake of these types of techniques is moderate, due to the cost required to purchase new machinery.[241] This can be partially offset as reducing ammonia loss through low-emission spreading increases nitrogen concentrations in manure, leading to agronomical benefits such as increased crop yield and reduced need for nitrogen fertilisers. Farmers can therefore see direct financial benefits after investing in low-emission spreading equipment, which could be highlighted to incentivise the investment.[242]

227 V.H. Smith et al. (2006).

228 UNECE (2015).

229 S. Bittman et al. (2014).

230 Technique in which slurry is deposited from hoses into narrow bands.

231 Technique using a shoe device to part crops and deposit manure onto the soil.

232 T.H. Misselbrook et al. (2002).

233 S.T.J. Lalor (2014).

234 R.J. Stevens et al. (1989).

235 P. Kai et al. (2008).

236 S. Bittman et al. (2014).

237 However, windless conditions can also lead to a build-up of high ammonia concentrations locally, which raises concerns for natural habitats in the vicinity.

238 J.J. Meisinger and D.W.E. Jokela (2000).

239 S.G. Sommer (1991).

240 UNECE (2015).

241 J.P. Newell Price et al. (2011).

242 Environment, Food and Rural Affairs Committee (2015).

Reducing fertiliser application can also further reduce ammonia emissions (see Section 3.5 on manufactured fertilisers). However, farmers will have to be convinced that it is worth learning a new technique[243] and investing in new equipment. The efficacy and the specific considerations of these various options are presented in Table 9.

Table 9. Percentage reduction of ammonia emissions by interventions in application of manure spreading, costs and considerations

Method	Percentage reduction of ammonia emissions (%)	Costs (£ per kg of NH_3 saved)[244]	Considerations[245]
Incorporation of manure	70–90 for immediate incorporation (within a few minutes) 45–65 for incorporation within 4 hours 30 for incorporation within 24 hours[246]	-£0.60 – +£2.30	Effectiveness varies depending on manure type (slurry or solid manure) Restricted to cultivated land
Lowering the pH of slurries to a stable level of 6 or less	50–60[247]	-£0.60 – +£1.20	
Band spreading	51–60[248,249]	-£0.60 – +£1.80	Efficiency dependent on crop height
Trailing hose	0–75; average 35[250,251]	-£0.60 – +£1.80	
Trailing shoe	28–74 average 65[252]	-£0.60 – +£1.80	
Injector	23–99 average; 70–80 depending on depth[253]	-£0.60 – +£1.80	Ineffective on shallow, dry, stony or compacted soil Effectiveness depends on injector type (shallow or deep, open or closed slots) and land type Application volume depends on size of slots

243 M.A. Sutton (2015).

244 All costing data from Bittman et al. (2014) converted to sterling and 2018 prices. Note that some interventions might result in benefits – e.g. through increased crop yields or lower fertiliser costs – once upfront costs are overcome (hence negative values within some ranges). Savings are relative to broadcast application.

245 UNECE (2015).

246 S. Bittman et al. (2014).

247 S. Bittman et al. (2014).

248 V. Eory et al. (2016).

249 C. Hani et al. (2016).

250 V. Eory et al. (2016).

251 J. Webb et al. (2010).

252 J. Webb et al. (2010).

253 J. Webb et al. (2010).

Although conservation of nitrogen in manure has positive effects on soil nutrient levels, this has been linked to increased release of nitrous oxide, another atmospheric pollutant. However, this has not always been observed and seems to depend on factors including weather conditions, injection depth, soil moisture and aeration.[254,255] Many studies have found substantial variations in the effectiveness of band spreading, trailing shoe and injection methods as different soil types, plant types, manure types and environmental conditions can influence effectiveness.[256,257]

3.5. Manufactured fertilisers

In addition to natural materials used as organic fertilisers, soils can be supplemented with non-organic fertilisers, which are artificially manufactured and contain minerals or synthetic chemicals. Nitrogen is the most abundant fertiliser used in the UK.[258] Globally, it is often spread as urea, a white crystalline solid containing 46 per cent nitrogen. Urea releases ammonia as it breaks down with the addition of water and an enzyme urease. This can occur in two to four days and happens more quickly on high-pH soils.

Rather than simply applying the urea fertiliser to the soil surface, there are ways to ensure that the nitrogen in the fertiliser is being absorbed and not lost to the atmosphere as ammonia. One way to limit the emissions coming from urea-based fertilisers is to not use too much fertiliser; a number of studies recommend that farmers not use excessive fertiliser, which can still be applied in a surplus of 25–50 per cent.[259,260,261,262] Another alternative is to reduce the overall use of manufactured fertiliser applied to crops, even below the economic optimum rate. A 20 per cent reduction in fertiliser nitrogen use would reduce crop yields by 2–10 per cent, an impact that could greatly affect small farms in particular. Soil analysis can be conducted to identify the optimum level of fertiliser to use. This can save money by reducing fertiliser costs and through healthier crops.

Other ways to limit ammonia emissions include the addition of a urease inhibitor,[263,264] or, as with manure, the fertiliser can also be physically mixed or injected into the soil quickly (within four to six hours of being applied) to maximise absorption by the soil.[265,266,267] Specific environments and weather conditions are also more likely to result in ammonia

254 J. Webb et al. (2010).
255 F. Bourdin et al. (2014).
256 T.H. Misselbrook et al. (2002).
257 K.A. Smith et al. (2000).
258 Defra and ONS (2018).
259 A.L. Collins et al. (2016).
260 T. Dalgaard et al. (2012).
261 UNECE (2015).
262 Y. Zhang et al. (2017).
263 UNECE. (2015).
264 Y. Zhang et al. (2017).
265 L. Loyon et al. (2016).
266 UNECE (2015).
267 Y. Zhang et al. (2017).

emissions from urea based fertilisers, so farmers are recommended not to use such fertilisers in warmer, dry and windy weather.[268]

Urea or urea-based fertilises can be replaced with another form of manufactured fertiliser, such as ammonium nitrate. Urea-based fertilisers hydrolyse to form ammonium carbonate. This increases the pH of the soil, thereby increasing ammonia emissions. With ammonium nitrate, ammonium and ammonia are at equilibrium at a lower pH, thereby reducing the levels of ammonia emission. Switching fertilisers entirely from urea to ammonium nitrate can be as much as 10–30 per cent more expensive than a urea-based fertiliser.[269] Table 10 shows the costs in this context may result from differences in fertiliser costs, but also investment in different applicators, use of heavier tractors or more labour time, and through maintenance of equipment. However, it should be noted that sometimes these approaches may result in decreases in fertiliser and application costs because they promote greater efficiency in nitrogen use.[270]

Table 10. Reduction of ammonia emissions by interventions in application of non-organic fertilisers

Method	Reduction of ammonia emissions (%)	Costs (£ per kg of NH_3)[271]	Likely uptake[272]
Mixing or injecting urea-based fertiliser directly into the soil quickly after application	50–90[273,274]	-£0.60 – +£2.30	Moderate, due to investment costs of new machinery, although 'high' fertiliser N prices are encouraging increased use, particularly via contractors
Applying urea fertiliser with a urease inhibitor	40–70[275,276]	-£0.60 – +£2.30	Low-moderate – education is required to ensure farmers are aware of the benefits to yield justifying the increased cost
Optimal weather conditions for spreading	Up to 5[277]	Not available	Moderate to high; however, farmers may be reluctant not to apply fertiliser N to 'wet' soils in spring to support early season crop growth
Replacing urea fertiliser with another nitrogen form (e.g. ammonium nitrate)	Up to 20[278]	-£0.50 – +£1.50	Low, as the main reason urea is used is due to the lower cost per unit of N – education is required to help farmers understand the potential yield losses from urea use due to reduced N efficiency

268 Y. Zhang et al. (2017).
269 S. Bittman et al. (2014).
270 S. Bittman et al. (2014).
271 All costs based on Bittman et al. (2014).
272 J.P. Newell Price et al. (2011).
273 L. Loyon et al. (2016).
274 UNECE (2015).
275 UNECE. (2015).
276 S. Bittman et al. (2014).
277 J.P. Newell Price et al. (2011).
278 J.P. Newell Price et al. (2011).

3.6. Other options

In addition to interventions at the main points in the agricultural processes around manure production and management, there are a number of other options for intervention mentioned in the literature. These include planting trees, reducing protein consumption in humans and the use of plants with increased nitrogen use. The impact of these other options on ammonia emissions detailed in Table 11.

Reduced consumption of protein by humans

Whilst protein is required as part of a healthy diet, estimates show that levels of animal protein in European diets are on average 70 per cent higher than recommended, and meat, milk and fish consumption has more than doubled globally since 1970. Changes to diet could potentially reduce ammonia emissions. For example, changes across Europe to a diet which consists of 63 per cent less meat and eggs would reduce ammonia emissions from animal production by 48 per cent.[279] Alternatively, a shift in the type of meat consumed could decrease ammonia pollution. For example, Steinfeld et al. (2010) advocate a shift from beef and pork to poultry and milk, whose production involves lower nitrogen costs.[280]

Use of woodland and tree planting

Arable/grassland could be converted to woodland, changing the use of the land. This would reduce emmisions by 90 per cent.[281] However, a permanent change of land use is unlikely to be adopted by farmers without significant financial incentive.

Another use of trees is to plant tree shelter belts around livestock housing and slurry storage facilities. These reduce the airflow around the buildings and also directly recapture some ammonia.[282]

Table 11. Percentage reduction of ammonia emissions by other possible methods for ammonia reduction

Method	Percentage reduction of ammonia emissions (%)
Planting a tree shelter belt	Up to 10[283]
Using plants with improved nitrogen use efficiency	Up to 10[284]
Changing land use from arable to woodland	Around 90[285]
Reduced consumption of meat and eggs by humans by 63%	48[286]

279 D.S. Reay et al. (2011).
280 H. Steinfeld et al. (2010).
281 J.P. Newell Price et al. (2011).
282 J.P. Newell Price et al. (2011).
283 J.P. Newell Price et al. (2011).
284 J.P. Newell Price et al. (2011).
285 J.P. Newell Price et al. (2011).
286 D.S. Reay et al. (2011).

4 Reflections

4.1. Interventions

As the evidence presented in Section 3 shows, there are a number of possible interventions which can be implemented to reduce ammonia emissions. No single intervention is an adequate solution to address all sources of emissions across different agricultural contexts. Rather, a range of interventions are likely to be necessary to fully address the challenge of ammonia emissions. There are various factors which influence the decision about which solutions would be optimal, including cost, emission reduction, strength of evidence, feasibility/acceptability, and proximity to sensitive ecosystems. An overview of some of these factors spanning the different methods is detailed in Figure 13.

Based on this analysis, we note that two interventions – floating crust on slurry stores and phase feeding –have been assessed as highly acceptable and indeed are already widely used. In addition, most of the interventions related to manure spreading (injection, band spreading and incorporation) seem to be moderately cost-effective (relative to other interventions) and moderately acceptable. It is also worth noting, based on the analysis in section 2.6, that damage to human health and biodiversity is equivalent to £3 per kg of ammonia produced (i.e. £1 in cost is incurred for every 0.3kg of ammonia produced). In this context, the majority of interventions could be considered cost-effective.

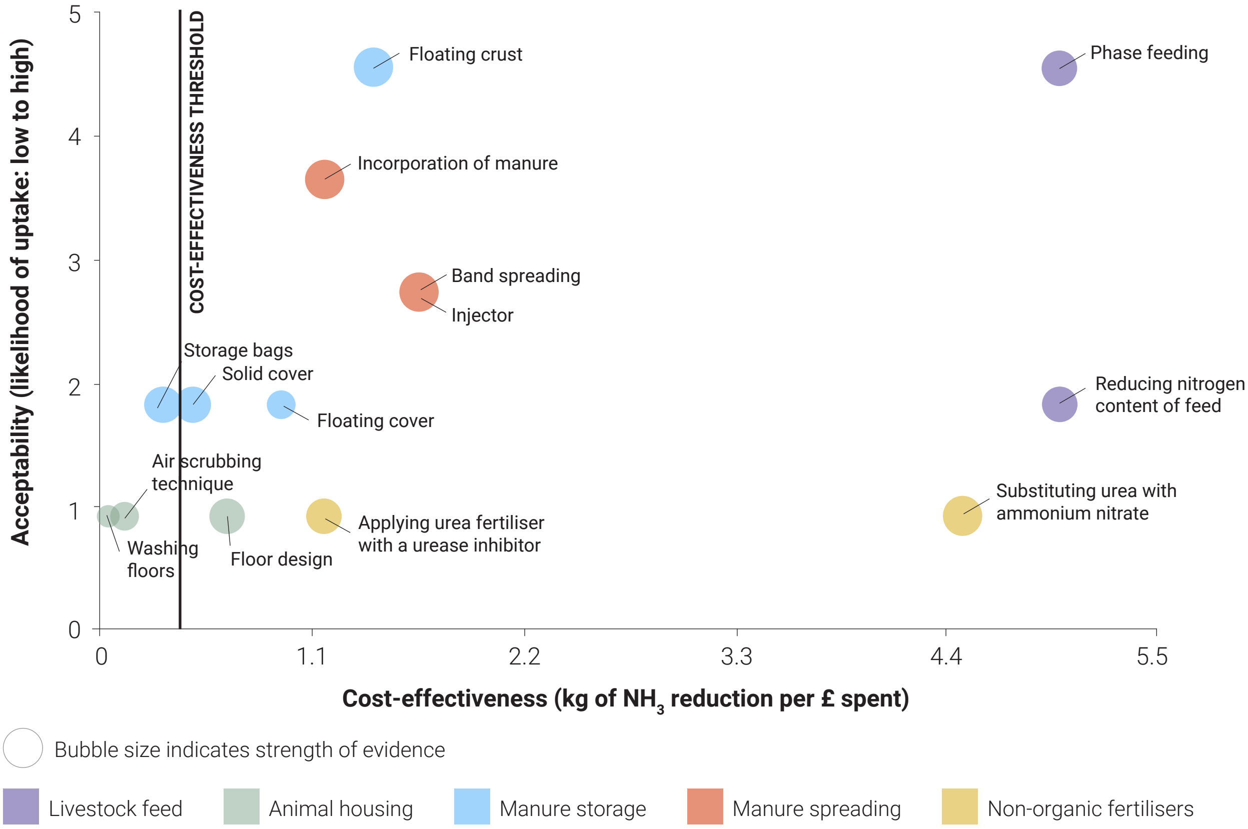
Interventions also need to be considered in the context of the whole ammonia lifecycle. If emissions are reduced at the point of manure production but then not reduced in later stages (e.g. in storage or in spreading), then the emissions benefits at earlier stages are negated. Therefore, interventions need to be used in combination spanning the whole lifecycle of manure production, storage and application. Implementing interventions only at the manure storage stage, for example, will not be effective if the losses prevented are then incurred instead through spreading practices. This also highlights the benefits of feed-based approaches, which reduce the amount of ammonia produced from manure from the outset.

4.2. Policy implementation

We identify above a number of potential actions that might be both cost-effective and acceptable based on the existing evidence. However, there still remains a question as to how these can be implemented in practice. Policymakers can help implement these changes through three main types of action:

- **Regulation:** Regulation can take place at different levels. At a high level, it can set targets for levels of emissions. At a more detailed level, regulation can guide the use

Figure 13. Bubble diagram showing strength of evidence, cost effectiveness and acceptability for a range of interventions to reduce ammonia emissions



Source: RAND Europe analysis. Cost-effectiveness and strength of evidence from Bittman et al. (2014). Acceptability based on likelihood of uptake from low (1) to high (5) as set out in Newell Price et al. (2011).

of specific practices, or limit the use of others.

- **Incentives:** Incentives can provide financial motivation to take particular actions. Examples include tax relief, or providing financial support to overcome upfront costs of implementing new techniques or purchasing new equipment. Some argue that incentive-based strategies are more attractive to practitioners than regulatory instruments, as they provide greater flexibility to the practitioners.[287]
- **Education:** Disseminating these messages and sharing learning about how to effectively implement new techniques can also help support implementation of new interventions. This could include developing peer-to-peer learning networks, updating training materials, or providing online or in-person training and support. In addition to informing the agricultural community, it

287 OECD (2007).

could be important to educate the public and, in turn, to drive the issue up the policy agenda. Educating the public may also influence other parts of the food chain (e.g. supermarkets or suppliers) or enable individuals to make informed choices about their level of meat and protein consumption, either overall or by changing the composition of their diet.[288]

Two European countries, Denmark and the Netherlands, provide useful examples of how interventions can be effectively implemented to reduce ammonia emissions. Although the interventions needed in these contexts may be quite different to the UK due to differences in farm types and ecosystem context, there is still potential to learn from the ways in which interventions have been implemented through policy. Table 12 maps the interventions implemented in each country into each of the three areas set out above.

Table 12. Interventions implemented in Denmark and the Netherlands to reduce ammonia emissions[289]

Country	Regulation	Incentives	Education
Netherlands	• Manure must be applied using low-emission spreading techniques. • Slurry stores must be covered. • New housing must meet low-emission criteria, through a certification scheme.	• Funding for manure banks to support transfer between farms. • Support for industry strategy to install low-emission housing. • Grants for research into innovative manure-management techniques. • Subsidies and tax breaks for new technologies.	• Peer-to-peer farmer networks for support and knowledge transfer.
Denmark	• Manure must be applied using low-emission spreading equipment and limited in winter. • Slurry stores must be covered. • Solid manure must be incorporated within 6 hours. • Permits required, including fertiliser plan for most farms. • Limiting amount of fertiliser available for purchase. • Setting nitrogen limits.	• Most EU rural development funding allocated to pollution. • Tax relief on mineral fertiliser to incentivise small farms to develop a fertiliser plan.	

288 O. Oenema et al. (2011).

289 Defra (2018).

In Denmark, a largely regulatory approach was taken from the outset, but this initial regulation was well aligned with existing trends in the sector and supported by farmers' organisations from the beginning.[290] In particular, many of the measures mandated were not too costly and overall were economically worthwhile for farmers to implement.[291] As such, the regulation was largely aligned with farmers' voluntary actions, but was effective in ensuring widespread implementation and compliance. Tax subsidies and incentives were also subsequently introduced, and have been important in supporting the uptake of measures with a greater upfront cost, such as restoration and replacement of housing and manure systems.[292] A strength of the Danish approach is that livestock production is coupled with requirements for agricultural land, meaning there is less need for transport of manure between farms. This avoids some of the issues seen elsewhere, for example in the Netherlands, where each truckload of manure transported must be tracked and monitored by the government, which is costly.[293]

An evaluation of the Dutch implementation of the European Union Nitrates Directive[294] found that although financial incentives can facilitate implementation of new technologies, awareness raising, practicability and risk perception are also important.[295] Van Grinsven et al. (2016) also suggest that allowing more flexibility in the ways in which nitrogen reduction is achieved might facilitate more innovation. However, it is also noted that while a largely regulatory approach has been effective (albeit with incomplete compliance in some cases), it has been costly for the agricultural sector, and consumers are typically unwilling to pay a premium for ammonia reduction in the same way they might for improved welfare practices or organic food.[296] This means that trade-offs need to be made by policymakers between agricultural profits and health and ecological wellbeing. It is suggested that some of the externality benefits could be passed onto farmers, but this may conflict with EU regulations in terms of competition policy. Actions taken at supranational level might be necessary to address disparities that might result from piecemeal implementation by different countries,[297] though it should be noted that local-level initiatives can also add value since they can be tailored directly to the local context and potentially may generate more buy-in.[298]

Overall, this suggests that interventions with a high level of acceptability to farmers and low upfront costs can be effectively implemented through regulation alone. Based on our analysis, this might apply to the use of phase feeding and incorporation of manure, for example. For those interventions which are less acceptable, education may be required, and where there are high upfront costs, financial support may be necessary. For example, using

290 T. Dalgaard et al. (2014).
291 B.H. Jacobsen (2004).
292 T. Dalgaard et al. (2014).
293 T. Dalgaard et al. (2014).
294 H.J.M. van Grinsven et al. (2016).
295 M.A. Dolman et al. (2014).
296 H.J.M. van Grinsven et al. (2016).
297 K. Bull et al. (2011).
298 P.H. Kahn (2001).

optimised nitrogen content in feeding appears highly cost-effective but has low acceptability, meaning that education might be a useful approach. It also should be noted that where interventions are costly to farmers, it cannot be assumed that these costs can be passed onto the consumer. This implies that costs may need to be borne by the agricultural sector or offset (wholly or partially) by government subsidies to the extent that is feasible under competition regulation. It may also suggest that there is a wider need for education, beyond the farming community, to raise the profile of ammonia emissions from agriculture and their impacts amongst other stakeholders, including food retailers and consumers.

4.3. Caveats and complexities

There are a number of caveats, limitations and complexities to this analysis. Firstly, from a methodological perspective, our analysis is based on a rapid evidence assessment rather than a full systematic review.[299] We have not covered all possible literature and it may be that we have missed some important evidence. Even within the material reviewed, we have not been able to reflect the full nuance and detail of the literature in this overview report. There are also limitations to the content of the review based on gaps in the literature, and caveats and complexities that should be taken into account. These are summarised below.

Impact of ammonia on biodiversity

- The evidence related to the impacts of ammonia emissions on animals and the wider ecosystem is very limited. Most research to date has focused on plant species, and a limited subset of UK habitats. It is therefore likely that the impacts of ammonia on biodiversity and ecosystems are even wider than we are able to document.
- We have also focused this review on the impacts on biodiversity. Understanding the effects of ammonia on ecosystem function is far more complex.
- It is difficult to separate the effect of ammonia from the effects of nitrogen pollution more generally. Where possible we have focused on ammonia; however, many studies do not separate these effects.
- We have identified limited evidence on capacity for recovery, and the nature and rate of recovery of habitats from ammonia pollution is not well understood.[300] For example, our understanding from discussions with experts is that Moninea Bog (see p.16) has been recovering since the polluting farm reduced its ammonia emissions, but these results are not yet published.
- There will also be lags in any biodiversity response to changes in ammonia emissions and deposition. Mosses and lichens may respond relatively rapidly (within five years), but other plants and soil processes may take much longer to recover.

Costing the impacts of ammonia

- There is no clear consensus on best way to cost impacts on biodiversity, and very few studies have been conducted to quantify these economic impacts.

299 For a full description of the methods used, refer to Appendix A.

300 N.B. Dise et al. (2011).

- Part of the reason for this is that the underpinning valuation evidence for this type of analysis is thin. There is limited evidence to value public willingness to pay for the preservation of the 'non-charismatic' species affected by ammonia.[301] Specifically in terms of ecosystem services analyses, it is challenging to cost many of the impacts from ammonia emissions. In addition, some of the elements that are easiest to cost may benefit from higher levels of ammonia, thus underestimating the economic impact of the detrimental effects of ammonia.

Acceptability of interventions

- The evidence on acceptability of interventions and their likelihood of uptake is based on a source from 2011.[302] It is likely that attitudes and practices have evolved since that time; however, we have not been able to identify more recent evidence across a range of interventions.

Interaction with other pollutants

- Reducing ammonia may have negative implications for carbon sequestration. Increases in nitrogen may reduce species richness, but they increase the overall volume of vegetation through promoting the growth of nitrogen-loving species, which can take in more carbon.
- There are also effects on other pollutants due to specific mitigation measures. For example, changes in fertiliser types and techniques for spreading can have implications for the level of emissions of other polluting gases, such as methane or nitrous oxide.
- This is also reflected in the likely changes in where the majority of ammonia is deposited. As regulation, for example on car emissions, comes into practice, it is likely that the levels of particulate matter from other sources will continue to fall. As this happens, the amount of ammonia that binds to particulate matter and travels long distances will fall. This is beneficial in terms of impact on human health. However, if the overall amount of ammonia produced remains consistent, this could lead to significant increases in the level of deposition in the vicinity of agricultural land and semi-natural habitats, which could have significant ecosystem implications.

Linking interventions to impacts on biodiversity

- There are very few studies specifically linking the effectiveness of interventions to their benefits for biodiversity. Evidence typically covers the effectiveness of interventions in reducing ammonia emissions, but rarely goes further to link specific interventions to their wider impacts on ecosystems. These are inferred based on the evidence in other studies on the impact of ammonia on biodiversity.
- It may be that some interventions are more or less effective in improving biodiversity outcomes separate from their effects on ammonia production, perhaps due to the timing or location of ammonia reductions.

301 Public willingness to pay depends on public sentiment with respect to how much they recognise and identify with a species, for example polar bear cubs often engage the public more than a species of plant or insect.

302 J.P. Newell Price et al. (2011).

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Appendix A. Methodology

A.1. Question setting

The topic and questions for the evidence synthesis were developed in consultation with key policy stakeholders in the Department for Environment, Food & Rural Affairs (Defra), Public Health England (PHE), and the Chief Scientific Advisors to the government. The initial decision to focus on air quality was taken by the Royal Society in discussion with their fellows. A number of possible topics in this area were then established in discussion with the fellowship and these were then presented to the Chief Scientific Advisors, who selected ammonia as a priority topic. We then refined this further by establishing the policy needs and ongoing work of PHE and Defra. The aim was to ensure that the work was useful, novel and added to rather than duplicated existing knowledge. Based on this, we established three main questions to focus our work:

1. What are the impacts of ammonia emissions from agriculture on biodiversity in the UK?
2. What interventions are available to reduce ammonia emissions from agriculture, and how effective are they?
3. How do the costs of implementing those interventions compare to the costs of inaction on ammonia emissions, both in terms of impacts on biodiversity and wider impacts (e.g. on human health)?

A.2. Literature review

To capture academic literature, the team performed searches of the Web of Science database using a search strategy devised to capture information relevant to each of the focus questions. The searches were conducted in English with a timeframe of 2008 to the date when the search was performed (May 2018). This returned a total of 4,852 results, including duplicates between the questions (Table 13).

Following the search, all articles were screened for inclusion based on their content using their titles and abstracts, and divided based on their geographic reach (UK and international). The screening process was trialled on a small sample of articles by the whole team, and each study was then screened by only one member of the team. In cases where team members were uncertain on the inclusion of an article, these articles were highlighted for discussion and reviewed by 1–2 other team members. The full text of the relevant UK articles was reviewed and details entered into the extraction table capturing information on the following:

- Bibliographical information on the article
- Type of data used
- Habitat covered
- Scale and type of farming
- Country or region of focus

Table 13. Search term strategy for Web of Science searches

Search	Terms	Results
1: For evidence on the impact of ammonia emissions on biodiversity, their measurement and the costs	(Ammonia OR particulates OR ammonium OR NH3) AND (Biodiversity OR species OR ecosystem* OR habitat*) AND (impact* OR effect* OR cost* OR economy* OR monet* OR capital) AND (Agri* OR farm*)	1,110
2: For evidence on the costs of implementing ammonia-reduction interventions	(Ammonia OR particulates OR ammonium OR NH3) AND (interven* OR polic* OR action* OR regulat* OR limit* OR reduc*) AND (cost* OR consequence* OR impact* OR econom* OR effect*) AND (Agri OR farm*)	2,640
3: For evidence on the impact of interventions to reduce ammonia on biodiversity outcomes	(Ammonia OR particulates OR ammonium OR NH3) AND (Biodiversity OR species OR ecosystem* OR habitat*) AND (interven* OR polic* OR action* OR regulat* OR limit* OR reduc*) AND (Agri OR farm*)	844
4: For specific evidence from certain countries on policies to reduce ammonia emissions	(Ammonia OR particulates OR ammonium OR NH3) AND (interven* OR polic* OR action* OR regulat* OR limit* OR reduc*) AND (Netherlands OR Holland OR Dutch OR Denmark OR Danish) AND (Agri OR farm*)	105
5: To capture wider evidence on impacts of nitrogen on biodiversity[302]	nitrate* OR nitrogen AND Biodiversity OR species OR ecosystem* OR habitat* AND impact* OR effect* OR cost* OR economy* OR monet* OR capital AND Agri* OR farm* AND UK OR United Kingdom OR Britain OR British OR England OR Scotland OR Wales OR Northern Ireland	153

- Background information on ammonia emissions and reduction
- Evidence on the effect/impact of ammonia emissions on biodiversity
- Interventions
  - Type of intervention
  - Evidence on intervention effectiveness
  - Evidence of impact of the intervention on biodiversity
  - Barriers and enablers to implementing interventions
- Costs
  - Evidence on implications of non-action
  - Intervention-specific cost information
- Article quality.

The extraction template was piloted for three articles by the whole team, and extraction was then conducted in parallel, with each article reviewed in detail by one member of the team.

Where appropriate, references from the articles reviewed in full-text form were added to the list of articles for review, in a snowballing process. In addition, relevant literature was suggested during key informant interviews, focusing in particular on including grey literature and policy documents, and also pre-publication materials.

303 This final search was added to ensure that nothing was missed in searching for ammonia rather than nitrogen. This was geographically bound to include UK references only because of the scale of the literature in this field. Thirty-one citations were found in both search 1 and search 5.

Table 14. Interviewees consulted during this project

Name	Role and organisation
Professor Mark Sutton	Environmental Physicist, Centre for Ecology & Hydrology, Edinburgh
Professor Laurence Jones	Group Leader: Wetlands, grasslands and croplands, Centre for Ecology & Hydrology, Bangor
Dr Carly Stevens	Senior Lecturer, Lancaster Environment Centre, Lancaster University
Dr Stefan Reis	Science Area Head: Atmospheric Chemistry Effects, Centre for Ecology & Hydrology, Edinburgh
Dr Keith Goulding	Soil Chemist: Sustainable Agriculture Sciences, Rothamsted Research
Dr Mike Holland	Freelance consultant, Ecometrics Research and Consulting (EMRC)

A total of 164 publications are included in this synthesis.

A.3. Key informant interviews

To complement our literature review, we interviewed six key experts in the field in a personal capacity (Table 14)[304] to provide a deeper understanding of the broader topic and understand the evidence for the impact of ammonia on biodiversity, as well as possible interventions and any associated costs. In addition, the experts provided suggestions of additional literature which we added to our review. Interviews were conducted by telephone using a semi-structured approach. The protocol used is provided in 0. Evidence from each interview was mapped against the three main study questions for analysis.

The interviews were conducted in parallel with the literature search. Interviewees were initially selected based on desk research and recommendations. However, once the initial literature search was completed, additional interviewees were selected based on key publications. The literature search was used as the basis of the report's structure and content, with the interviews used to clarify understanding and recommend supplementary literature sources.

A.4. Analysis

To analyse and combine the information from the different data-collection methods used in this study, the team held an internal workshop to review and triangulate the data. Each study question was assigned to two members of the team, who reviewed the extracted data from the studies and interviews related to that study and identified key findings and gaps in the evidence. These initial findings were presented to the full team at the start of the workshop, and were then supplemented by additional supporting information bringing in what different team members had discovered throughout the process to ensure no key evidence or observations were lost. The overall messages, focus and evidence gaps were then discussed with the team, and the overall structure and content of the report agreed. Detailed presentation of the data was then

304 Interviewees were identified via the professional networks of those conducting the review, via targeted online searches, and through recommendations from other interviewees.

conducted initially by one member of the team, before being reviewed by at least two further team members as part of an iterative process to ensure completeness and accuracy. The report was also shared with three subject matter experts for review, in addition to normal internal quality assurance processes.

A.5. Limitations and caveats of the methodology

This study is subject to a number of important caveats and limitations, including the following:

1. The literature review was a rapid evidence assessment rather than a systematic review. This means we did not cover all possible literature. However, the review included a diverse set of carefully selected articles, informed by expert guidance, and therefore paints a wide-ranging picture of the state of play with respect to ammonia emissions from agriculture and their impacts on biodiversity. However, we may have missed some relevant literature based on the nature of our searches and time constraints.
2. We have not been able to reflect the full complexity of the literature in this overview report. The aim of this report is to provide a concise, policy-relevant overview of the key issues and evidence. Inevitably, there are many details and nuances that could not be included given the scope and length of this study.
3. We conducted interviews with key experts in the UK. However, we only spoke to a sample of individuals working in the field; therefore, the information provided may not be representative of all researchers in the relevant fields, or the full range of work conducted (particularly in an international context, since we focused on UK academics).
4. The interviews were semi-structured, meaning that not all interviewees were asked identical questions. In addition, all the results from interviews are based on the knowledge and perceptions of the participants, and it is not possible to verify every piece of information provided. Additionally, the interviews were carried out by multiple interviewers; therefore, different styles and approaches will have been used. We tried to mitigate against this by developing standardised protocols for the interviews. All interviews were written up as comprehensive notes rather than a verbatim transcript, meaning that some information may have been lost. To minimise this risk, all interviews were conducted in pairs, with the notes verified by both interviewers once they had been written up.
5. Available evidence in some areas is thin, or subject to debate, which limits the extent of our analysis and the degree to which our findings can be concrete. In particular, there is little evidence on the acceptability of interventions to farmers, and ongoing debate and challenges around the measurement of the biodiversity costs from ammonia emissions. We have attempted to reflect this uncertainty and the strength of the evidence in the report.

Appendix B. Key informant interview protocol

Introduction

The Royal Society and RAND Europe are working together to conduct a rapid evidence synthesis on the impacts of ammonia emissions from agriculture on biodiversity. The aims of the work are to:

1. Pilot a set of principles for good evidence synthesis for policy (developed by the Royal Society and the Academy of Medical Sciences) on a real world problem.
2. To collect evidence to support policymaking relating to the air quality strategy and post-Brexit future of the countryside discussions.

The work will be conducted over the next 3 months and the outcomes of the study will be made publicly available and disseminated among policymakers by the Royal Society during summer 2018.

As part of the project, we are conducting key informant interviews with experts on the topic to test our understanding, ensure we have identified key literature and also supplement our search with unpublished data or relevant sources beyond academic journal articles.

The project will be written up as a public report which will be available on Royal Society and RAND websites, and should be completed by late summer 2018.

Do you have any questions about the project?

Data protection

With your permission I would like to record this interview, but the recordings, any notes and transcripts will be kept strictly confidential and never be made available to any third party.

Any quotes included in RAND Europe's final report will not be explicitly or directly attributed to you without your permission. Should we wish to use a quote which we believe that a reader would reasonably attribute to you or your organisation, a member of the RAND Europe project team will contact you to inform you of the quote we wish to use and obtain your separate consent for doing so.

All records will be kept in line with the General Data Protection Regulation (GDPR) 2018. Further information about RAND Europe's data security practices can be provided upon request.

To keep all processes in line with the GDPR 2018, we would like to ask you to confirm a few data protection statements:

1. Do you agree that the interview can be recorded by RAND Europe and that these recordings can then be transcribed for the purpose of providing an accurate record of the interviews?

   Yes ☐ No ☐

2. Do you agree that RAND Europe can store this data securely on password-protected

computers and its servers for the duration of the project?

Yes ☐ No ☐

3. Do you agree that RAND Europe can destroy the recordings and all notes and transcripts after the project has been completed?

   Yes ☐ No ☐

4. Do you agree to us recontacting you if we wish to use a quote which we believe that a reader would reasonably attribute to you or your organisation?

   Yes ☐ No ☐

Background

- What is your background and experience related to ammonia and biodiversity?

Impact of ammonia emissions on biodiversity

- What in your view are the biggest impacts of ammonia on biodiversity? (might need to clarify – within which species/habitats?)
- How do the impacts vary by farm type?
- Can the impacts be quantified?
- Do you know any key publications on this topic that we should definitely include?
  - Prompt: are there key publications within the grey literature e.g. from NGO's, policymakers or others that we should consider?

Options for intervention

- What are the key options for intervention to reduce the amount of ammonia emissions from agriculture?
  - Might want to prompt: slurry management, livestock numbers…
- How effective are these interventions?
- How does this differ by farm type?
- What are the challenges in implementing these interventions? What are the possible enablers?
- Are there any key publications on this?

Costs of action and inaction

- What evidence is available on the costs of implementing the different interventions?
  - Costs to farmers
  - Costs to the government
  - Have any of them been costed from a UK perspective?
- What are the costs of ammonia pollution in terms of the impact on biodiversity? Impact on human health? What evidence is available that could support an economic analysis?
- Are there any key publications on this?

Any other comments

- Are there any other key issues that we haven't covered that you would like to highlight?
- Is there anybody you think would be particularly relevant for us to speak with?