Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP)
Sustainable Farming Scheme Evidence Review
Technical Annex

Annex 8: Improving air quality and well-being

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Client Ref: Welsh Government / Contract C210/2016/2017
Version 1.1
Date 04/07/2019

Funded by:
Llywodraeth Cymru
Welsh Government
Canolfan Ecoleg a Hydroleg
Cyngor Ymchwil yr Amgylchedd Naturiol
Centre for Ecology & Hydrology
Natural Environment Research Council

Series	Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP) - Sustainable Farming Scheme Evidence Review (WP11), Technical Annexes
Title	Technical Annex 8: Improving air quality and well being
Client	Welsh Government
Client reference	C210/2016/2017
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How to cite (long)	Jones, L., Bealey, B., Braban, C., Martineau, H., Williams, A. & Dragosits, U. (2019). Technical Annex 8: Improving air quality and well-being. In *Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP): Sustainable Farming Scheme Evidence Review*. Report to Welsh Government (Contract C210/2016/2017). Centre for Ecology & Hydrology Project NEC06297.
How to cite (short)	Jones, L. et al. (2019). Annex 8: Improving Air Quality and well-being. ERAMMP Report to Welsh Government (Contract C210/2016/2017) (CEH NEC06297)
Approved by	Chris Bowring James Skates

Version History

Version	Updated By	Date	Changes
0.1	LJ	31/5/2019	Initial draft.
0.2	WG	18/6/2019	Responses from WG
0.3-0.5	LJ	26/6/2019	Edit to WG comments
1.1	PMO	4/7/2019	For publication

Contents

1 Introduction

To review the implications of potential interventions relevant to air quality impacts on ecosystems and human health. The review should cover the following components: the main pollutants and their interactions, how far pollutants are transported (and by extension, how far benefits from reductions in pollutant concentrations may be realised), thresholds for impacts, considerations for optimising the benefits from these interventions.

2 Outcomes

The intended outcomes of interventions to reduce pollutant ammonia emissions at source or to capture some of it during the pathway between the source and environmental or human receptors are:

- **Lower concentrations of pollutants in the atmosphere:**
  This results in a direct reduction of the pollutant concentration - with the focus on ammonia in this review, which subsequently affects secondary particulate matter concentrations.

- **Fewer habitats, ecosystems and species affected by reactive atmospheric nitrogen:**
  The lower concentrations of ammonia lead to a reduction in direct effects of gaseous ammonia toxicity on sensitive ecosystem components, and a reduction in the deposition flux of reduced-nitrogen compounds in rainfall and cloud droplet deposition. Together this will reduce the pressure on the wide range of semi-natural ecosystems in Wales that are sensitive to atmospheric nitrogen deposition.

- **Reduced exposure of people to harmful air pollutants:**
  The reduction in secondary fine particulate matter (PM2.5) which results from chemical reactions with ammonia in the air will benefit people living in Wales. There is no safe level of particulate pollution, therefore any reduction in PM2.5 concentrations will have health benefits for people living in Wales.

3 Policy Relevance and Policy Outcomes

How do these outcomes align to the Well-Being of Future Generations Act well-being goals and national indicators, the Sustainability and Management of Natural Resources principles in the Environment (Wales) Act and Natural Resources Policy (NRP) priorities?

The outcomes align to the following priorities (in bold)

- ***Increased canopy cover and well located woodland, for example close to towns and cities where it will have the greatest recreational and ecosystem service value***
- *Maintaining, enhancing and restoring floodplains and hydrological systems to reduce flood risk and* ***improve water quality*** *and supply; (including catchment management approaches, natural flood management, soil management etc.)*
- ***Restoration of our uplands and managing them for biodiversity, carbon, water, flood risk and recreational benefits***
- *Resilient ecological networks*
- ***Increasing green infrastructure in and around urban areas***
- *Coastal zone management and adaptation*

4 Overview of the pressure

4.1 Introduction

Air pollution, consisting of anthropogenically driven emissions of gases and particulate matter (PM) to the atmosphere, chemical processing in the atmosphere and subsequent deposition/uptake/inhalation is a global issue that has substantial adverse impacts on both the environment and on human health (Galloway et al., 2008; Oenema et al., 2011; Lim et al. 2012).

Atmospheric pollution has a significant influence on human and ecosystem health. Inhalation of ozone (O_3) and particulate matter has been linked to cardiovascular and respiratory diseases (WHO, 2006, 2013a). Deposition of acidic gases causes acidification of terrestrial and aquatic ecosystems, and nitrogen (N) deposition e.g. from nitrogen oxides (NO_x) or ammonia (NH_3) leads to eutrophication (Sutton et al., 2011a, b; RoTAP, 2012) and plant species composition change in naturally N-limited ecosystems. This latter impact is currently of wide concern for UK ecosystems, particularly those adjacent to intensive farming activities.

The Welsh Government is currently in the process of drafting the Wales Clean Air Plan. That document will focus on human health in more detail. This review focuses primarily on agricultural emissions of NH_3, with additional focus on the pollution removal capacity of woodland in general.

4.1.1 What are the main air pollutants affecting ecosystems

Nitrogen and sulphur compounds are among the most important air pollutants that can directly impact ecosystems. Sulphur (S) contributes primarily to acidification. However, although combustion derived sulphur dioxide (SO_2) was the major pollutant of concern for ecosystem impacts in the 1980s, UK emissions have reduced by >90% since their peak in the 1970s and it is no longer a major contributor to either ecosystem or human health impacts. Nitrogen has replaced sulphur as the main acidifying compound in the UK (RoTAP 2012). Although ammonia is alkaline, it is oxidised to nitric acid. NO_x are also acidic, so that reactive N also acidifies land and water (CML, 2016).

Although emissions of NO_x have decreased significantly, there are still significant emissions from transport and industry. NH_3 emissions only slightly declined in the past 20 years, but have been increasing again in the period 2014-2016 (NAEI 2018). NH_3 remains of major environmental concern due to adverse effects on forests, species composition of semi-natural ecosystems and soils.

4.1.2 What are the main air pollutants affecting human health

Air pollution is a major cause of death and contributes to the burden of non-communicable diseases globally (Lim et al., 2012), particularly in high population density megacities and countries experiencing rapid industrial expansion (Liu et al. 2017). Wales clearly does not have megacities and industry has declined, but the principle still applies and air pollution is still at levels which have clear human health impacts, and which exceed WHO guidelines.

Pollutants which affect human health in the UK include gases which such as nitrogen dioxide (NO_2) and ozone (O_3), and particulate matter (PM) (Carnell et al. 2019).

Particulate matter (PM) is an atmospheric component associated with premature mortality and morbidity. The World Health Organization (WHO) Review of the Health Aspects of Air Pollution (WHO, 2013b) concludes that the long-term health effects are not simply the sum of those from exposures to high concentration episodes of PM. At present, however, the WHO, and the UK Committee on the Medical Effects of Air Pollution (COMEAP), conclude that there is insufficient evidence to differentiate the components of PM that are more closely associated with different health effects (COMEAP, 2016; WHO, 2013b).

4.1.3 Sources of air pollutants and Interactions among pollutants, primary and secondary PM, etc.

Sources of air pollution cover all aspects of human activity including industry, transport, energy production, agriculture, waste processing, domestic activity (including cooking and biomass burning).

Primary pollutants are those directly emitted by either natural (biogenic) or human (anthropogenic) activities. Secondary pollutants are those formed by reaction or transformation in the atmosphere.

Atmospheric ammonia (NH_3) is a primary pollutant emitted by agricultural activities and, to a lesser extent by processing of organic materials (e.g. anaerobic digestion), transport and industry. The main sources of ammonia from agriculture are (in roughly descending order) manure spreading, animal housing, manure storage, grazing livestock and fertiliser application (especially urea and urea-ammonium nitrate), NAEI (2019). Sulphur dioxide (SO_2) is generated from combustion processes, and “NO_x” is the primary oxidised nitrogen pollution emitted from energy production and transport combustion process, and other industrial activities. Road fuels have, however, been desulphurised for many years and coal burning power stations implement flue gas desulphurisation.

Particulate matter (PM) includes particles of different size fractions, from a range of primary and secondary sources. Primary particulate matter (PM) can be emitted directly from many processes – particular examples include black carbon from combustion processes, and dust from dry soils. PM can contain a wide range of chemical components ranging from minerals to organic compounds, e.g. ammonia and NO_x can react together to form nucleation sites in particle generation.

Secondary pollutants of concern include ozone formed by photochemical reactions with other pollutants. NH_3 is the major precursor for neutralization of primary atmospheric acids SO_2 (and SO_x) and NO_x. The reaction produces secondary particulate matter (e.g. ammonium nitrate and ammonium sulphate salts) in the condensed phase. These reactions facilitate the long-range transport distance of pollution via secondary particles. Secondary PM can be semi-volatile which means the particle can evaporate under warmer conditions or return to the PM phase under colder atmospheric conditions.

Harrison et al. (2012) showed that, in 2009, the highest $PM_{2.5}$ concentrations in the UK generally occurred in winter, and were associated with easterly winds transporting air masses from mainland European emission sources, demonstrating the substantial regional contribution to $PM_{2.5}$ concentrations in the UK. The UK Air Quality Expert Group (AQEG, 2012) showed that, in 2010, winter made the largest seasonal contribution to annual average $PM_{2.5}$ concentrations. Both high wintertime and summertime $PM_{2.5}$ episodes, produced by build-up of local emissions during stagnant conditions, and the transport of secondary PM from continental Europe, respectively, also made important contributions to annual average $PM_{2.5}$ (AQEG, 2012).

4.1.4 Interactions among emission sectors

The atmospheric lifetime of pollutants and how far they get transported vary widely, with NH_3 having a short gas phase lifetime with rapid deposition on surfaces or conversion to ammonium (NH_4) and inclusion in PM, and SO_2 generally having a relatively long atmospheric lifetime with slow deposition and reaction onto sulphate in PM. However, the atmospheric lifetime and hence transport distance also depends on the meteorological conditions and climate of the local atmosphere.

Ammonia is predominantly from agriculture and is thus rurally based. Most NO_x and SO_x emissions are from combustion, which tend to be focused more in urban areas or main roads. Particulate generation from these sources is thus most likely where the land types meet and if the sources are strong enough. The geography and farming scale mean that some of the problems of air quality in cities like Los Angeles will not be as acute in Wales, but still are responsible for damage to ecosystems and impacts on human health.

4.2 Impacts of air pollution

4.2.1 Summary of main effects on ecosystems – terrestrial & freshwaters

Nitrogen is a basic nutrient required for growth, and most semi-natural systems are N-limited (Vitousek et al., 1997). Increased N deposition, especially during the last 70 years, has caused widespread adverse impacts on biodiversity and biogeochemical cycling in semi-natural systems. For example, plant diversity at sites receiving high atmospheric N deposition in the UK is typically 50% lower than sites receiving low levels of N (Maskell et al., 2010; Stevens et al., 2004; Field et al. 2017). Decades of research have catalogued the impacts of N deposition on natural systems (e.g. Pardo et al., 2011; Phoenix et al., 2012).

Nitrogen impacts are manifest through three principal mechanisms: eutrophication, acidification and direct toxicity (Bobbink et al., 2010). Sulphur impacts occur mainly through acidification and direct toxicity.

Eutrophication of oligotrophic (i.e. nutrient poor) habitats occurs where there is excess nutrient availability, above the natural, pre-industrial levels. Since N is a nutrient, any addition via atmospheric deposition increases the quantity of available N in the soil, stimulating plant productivity and rates of nutrient cycling in N limited terrestrial and aquatic systems (Vitousek et al., 1997). Changes in primary productivity and accumulation of N in soils (Jones et al., 2008) subsequently affect other soil or water mediated processes such as N leaching, or biological processes including flowering, alteration of competitive relationships between species, nutrient imbalances or N saturation, and indirect impacts mediated by changes in stoichiometry (Clark and Tilman 2008; Sala et al., 2000). These in turn affect biodiversity, and have a range of impacts on provisioning, regulating and cultural ecosystem services.

Reactive nitrogen contributes to acidification of soils and freshwater systems. Historically this acidification was primarily due to high sulphur deposition. However, since sulphur deposition has declined dramatically across Europe, N now makes a greater contribution to acidity than sulphur at current deposition levels (ROTAP 2012). Uptake and assimilation of ammonium by plant roots and the process of nitrification, and subsequent leaching of nitrate cause acidification of the soil (Gundersen and Rasmussen 1990). Acidification impacts occur through toxicity effects on aquatic and terrestrial organisms due to exceedance of biological and chemical thresholds of soil pH, and increased mobilisation of toxic ions such as Al_3^+ (aluminium). Effects on plant growth also occur through soil pH controls on phosphorus (P) availability (Kooijman et al., 1998), which indirectly alters plant productivity. Impacts occur directly through lowered soil pH and slower rates of biogeochemical cycling and organic matter decomposition, and through changes in the abundance or diversity of organisms such as fish or changes in plant growth and community composition.

Direct toxicity is caused by the gaseous forms of N as ammonia or as NOx. At very high concentrations, nitrogen dioxide (NO_2) is toxic to plant growth, but in many cases the toxicity is due to chronic exposure, i.e. annual dose, rather than acute toxicity. In much of Europe, concentrations of NO_2 are below the critical levels for plant growth defined in LRTAP Convention (2010), with the exception of some urban areas or close to major roads and large point sources. Ammonia is also toxic to plant growth at high concentrations. The majority of toxicity impacts are mediated by reduced plant growth, with some indirect effects on species composition and on biogeochemical cycling. Note that altered nutrient cycling may have positive or negative effects on greenhouse gas emissions.

4.2.2 Summary of main effects on human health

The health impacts include respiratory illness, cardio-vascular complications, a loss of life expectancy and premature deaths. Air pollution is rarely the sole cause of death but often exacerbates existing health conditions. Nonetheless it poses a serious health risk, with considerable cost to society (Cohen et al. 2005).

Most health impacts of particulate matter are attributed to fine particles with a diameter less than 2.5 microns ($PM_{2.5}$), which are small enough to travel deep into the lungs. Ammonia can be a substantial component of secondary $PM_{2.5}$ material, and is currently considered as damaging to human health as other particulate matter of the same size. PM_{10} (less than 10 micron diameter) can also worsen the symptoms of asthma (Donaldson et al., 2000).

Nitrogen oxides (NO and NO_2) cause increased likelihood of respiratory problems. Sulphur dioxide (SO_2) is an irritant to mucous membranes and can exacerbate health conditions like asthma, Ozone (O_3) is a powerful oxidant, causing damage to lung tissue and is a cause of premature deaths.

4.2.3 Thresholds for impacts

Critical loads and critical levels are the main thresholds that apply to N and S pollution impacts on ecosystems. Critical loads and levels are currently used as the main tool in assessment work for determining the risk of air pollution impacts to ecosystems.

4.2.3.1 Definitions

A critical load is 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*"[1]

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*".[1]

It is important to distinguish between critical loads (related to the quantity of a pollutant **deposited** from atmosphere to the surface and critical level (related to the gaseous **concentration** of a pollutant in the air).

4.2.3.2 Critical loads for nutrient nitrogen

Numerous manipulation experiments have been carried out where researchers add specific amounts of N (in different forms) and quantify the ecological responses, , especially in the EU, US, and Asia (Bobbink et al. 2010, Bobbink et al. 2011, Pardo et al. 2011). They have a number of limitations in that they are costly to implement over large scales and for many ecosystems and locations, under different climates, in a systematic way, and across an appropriate range of N deposition (it is difficult to find ‘clean’ areas in which to site N deposition experiments for some habitats). However, they also have considerable strengths, in that they are able to isolate other factors and address solely the issues of increased N load, and are able to experimentally assess interactions of N effects with management, with other nutrients, and with different forms of N.

Empirical critical loads for nutrient nitrogen are set under the UN ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). They are based on empirical evidence, mainly observations from manipulation experiments and gradient studies (Bobbink et al. 2010, Bobbink et al. 2011). Manipulation experiments allow for known doses of nutrients or concentrations of e.g. ammonia gas to be applied onto a habitat where changes in vegetation and soil properties can be monitored. Experiments should be of long duration, and use realistic treatments or dosing concentrations, applied at frequent intervals to mimic natural deposition to a reasonable degree. Critical loads are assigned to habitat classes of the European Nature Information System (EUNIS) to enable consistency of habitat terminology and understanding across Europe. Critical loads are given as ranges (e.g. 10-20 kg N ha^{-1} yr^{-1}). These ranges reflect variation in ecosystem response across Europe. An indication of the confidence in the critical loads is given by an uncertainty rating (reliable, quite reliable and expert judgement). Reliability ratings are derived from the body of research available for each habitat.

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[1] https://www.umweltbundesamt.de/en/publikationen/manual-on-methodologies-criteria-for-modelling

4.2.3.3 Acidity critical loads for terrestrial ecosystems

Two methods are used for calculating acidity critical loads for terrestrial habitats in the UK (Hall et al. 2011): an empirical approach for non-woodland habitats and a simple mass balance (SMB) equation for both managed and unmanaged woodland habitats. The SMB equation is the most commonly used model in Europe for the calculation of acidity critical loads for woodland ecosystems. This model is based on balancing the acidic inputs and outputs from a system, to derive a critical load which ensures that a critical chemical limit (related to effects on the ecosystem) is not exceeded. All of these methods provide critical loads for systems at steady-state.

4.2.3.4 Acidity critical loads for freshwater ecosystems

For freshwater ecosystems, the UK national critical load maps are currently based on the First-order Acidity Balance (FAB) model. FAB is a catchment-based model used to derive linked critical loads of S and N. Freshwater critical loads are based on data from a national survey of lakes or headwater streams, where a single site, judged to be the most sensitive (in terms of acidification) was sampled in each 10 km grid square of the country. In less sensitive regions (e.g. southeast England) the sampling generally consisted of one site in each 20 km grid square.

4.2.3.5 Critical Levels

Critical Levels for air pollutants are not habitat specific, as in critical loads, but have been set to cover broad vegetation types (e.g. forest arable, semi-natural), often with separate critical values set for sensitive lichens and bryophytes (see Table 4.2.3.5.1). Critical levels for the different pollutants have been derived from experiments and observation that show varied effects on vegetation including visible injury symptoms of exposure (e.g. leaf discolouration and leaf loss), and species composition changes in semi-natural vegetation. The ammonia critical level for vegetation is set at an annual mean of 3 µg m^{-3} to protect semi-natural vegetation, and 1 µg m^{-3} to protect sensitive lichens and bryophytes (Cape et al., 2009).

Pollutant	Receptor	Time Period	Critical Level	Reference
NO_X	All	Annual mean	30 µg/m^3	WHO[2], CLRTAP[3], AQ Directive[4]
NO_X	All	24 hour mean	75 µg/m^3	WHO, CLRTAP, AQ Directive
SO_2	Crops	Annual mean	30 µg/m^3	WHO, CLRTAP
SO_2	Forests and natural Vegetation	Winter mean (1 Oct to 31 Mar)	20 µg/m^3	WHO, CLRTAP
SO_2	Forests and natural Vegetation	Annual mean	20 µg/m^3	WHO, CLRTAP, AQ Directive
SO_2	Sensitive lichens	Annual mean	10 µg/m^3	WHO
Ammonia	Lichens and bryophytes (where they form a key part of the ecosystem integrity)	Annual mean	1 µg/m^3	CLRTAP
Ammonia	Other vegetation	Annual mean	3 µg/m^3 (with an uncertainty range of 2-4 µg/m^3)	CLRTAP

Table 4.2.3.5.1. Critical levels of air pollutants.

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[2] http://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf
[3] https://www.umweltbundesamt.de/en/cce-manual
[4] http://ec.europa.eu/environment/air/quality/existing_leg.htm

4.2.3.6 Human health limits

Although it is widely considered that there are no safe limits of air pollution for human health, guideline limits are applied. National air quality objectives have been set out for the UK based on European Directive limit and target values for the protection of human health (**Table 4.2.3.6.1**).

Pollutant	**Applies**	**Objective**	**Concentration measures as**	**Date to be achieved by**	**European obligations**	**Date to be achieved by**
Particles (PM_{10})	UK	50µgm-3 not to be exceeded more than 35 times a year	24 hour mean	31/12/04	50µgm^{-3} not to be exceeded more than 35 times a year	1/1/05
	UK	40µgm^{-3}	Annual mean	31/12/04	40µgm^{-3}	1/1/05
	Indicative 2010 objectives for PM_{10} (from the 2000 Strategy and 2003 Addendum) have been replaced by an exposure reduction approach for $PM_{2.5}$ (except in Scotland – see below)					
	Scotland	50µgm^{-3} not to be exceeded more than 7 times a year	24 hour mean	31/12/04		
	Scotland	18µgm^{-3}	Annual mean	31/12/04		
Particles ($PM_{2.5}$) Exposure Reduction	UK(excl Scotland)	25µgm^{-3}	Annual mean	2020	Target value25 µgm^{-3}	2010
	Scotland	12µgm^{-3}		2020	Limit value25 µgm^{-3}	2015
	UK urban areas	Target of 15% reduction in concentrations at urban		Between 2010 and 2020	Target of 20% reduction in concentrations at urban background	Between 2010 and 2020

Pollutant	**Applies**	**Objective**	**Concentration measures as**	**Date to be achieved by**	**European obligations**	**Date to be achieved by**
		background				
Nitrogen dioxide	UK	200µgm^{-3} note to be exceeded more than 18 times a year	1 hour mean	31/12/05	200µgm^{-3} not to be exceeded more than 18 times a year	1/1/10
	UK	40µgm^{-3}	Annual mean	31/12/05	40µgm^{-3}	1/1/10
Ozone	UK	100µgm^{-3} not to be exceeded more than 10 times a year	8 hour mean	31/12/05	Target of 120µgm^{-3} not to be exceeded more than 25 times a year averaged over 3 years	21/12/10
Sulphur dioxide	UK	266µgm^{-3} not to be exceeded more than 35 times a year	15 minute mean	31/12/05		
	UK	350µgm^{-3} not to be exceeded more than 35 times a year	1 hour mean	31/12/04	350µgm^{-3} not to be exceeded more than 35 times a year	1/1/05
	UK	125µgm^{-3} not to be exceeded more than 35 times a year	24 hour mean	31/12/04	125µgm^{-3} not to be exceeded more than 35 times a year	1/1/05
Polycyclic Aromatic Hydrocarbons	UK	0.25ngm^{-3}B[a]P	As annual average	21/12/10	Target of 1ngm^{-3}	31/12/12

Pollutant	Applies	Objective	Concentration measures as	Date to be achieved by	European obligations	Date to be achieved by
Benzene	UK	16.25 μgm^{-3}	Running annual mean	31/12/03		
	England and Wales	5μgm^{-3}	Annual average	31/12/10	5 μgm^{-3}	1/1/10
	Scotland	3.25μgm^{-3}	Running annual mean	31/12/10		
1,3-butadiene	UK	2.25μgm^{-3}	Running annual mean	31/12/03		
Carbon monoxide	UK	10mgm^{-3}	Maximum daily running 8 hour mean/in Scotland as running 8 hour mean	31/12/03	10mgm^{-3}	1/1/05
Lead	UK	0.5μgm^{-3}	Annual mean	31/12/04	0.5 μgm^{-3}	1/1/05
	UK	0.25μgm^{-3}	Annual mean	31/12/08		

Table 4.2.3.6.1. UK National Air Quality Limits for human health

5 Interventions

The following interventions have been reviewed:

- Primary measures: reducing nitrogen emissions at source
- Secondary measures: woodland planting and vegetation management to remove (already emitted) pollutants from the atmosphere

5.1 Reducing nitrogen emissions at source

5.1.1 Ammonia Abatement Techniques

Managing nitrogen (N) losses on the farm and improving N use efficiency (NUE) are the key components for overall reduction in NH_3 emissions. For example, on mixed livestock farms, between 10% and 40% of the N loss is related to NH_3 emissions (Oenema et al., 2012). Annex IX in the revised Gothenburg Protocol of CLRTAP lists the measures for controlling NH_3 emissions from agricultural sources.

An integrated approach, rather than focusing on a single stage of the manure management process (housing, manure storage and spreading), is required as controlling emissions from all aspects of farming is vital if it is to be cost-effective. For example, reducing emissions from livestock housing and storage preserves more N in the manure, which results in greater N losses during land spreading if high-emission techniques such as splash plate application is used. If, however, low emission techniques such as injection, trailing shoe or trailing hose are used, more of the N applied is available for uptake by crops and grassland. Annex IX emphasises this by stating that “Each Party shall take due account of the need to reduce losses from the whole nitrogen cycle”.

Techniques have developed over time with certain EU countries taking the lead and currently practising these methods (e.g. The Netherlands and Denmark). Best Available Techniques (BAT) have also been set out in the EU for pig and poultry farming under the Industrial Emissions Directive (IED, successor to the IPPC Directive). The Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs (BREF 07.2003) lays out BATs for on-farm processes and activities including nutritional feeding, feed preparation, rearing (housing), and collection, storage and spreading of manure.

Including the above from BREF, focus can be placed on five broad areas where ammonia abatement has already been well researched and proven as an effective method. These are:

- Livestock feeding strategies promote the use of low protein livestock feed to reduce the volatilisation potential of NH_3 in faeces.
- Decreasing ammonia emissions from animal housing involves reducing the surface area fouled by manure, e.g. through using slatted floors; increased use of straw or other bedding materials; rapid separation of faeces and urine; lowering the indoor temperature and ventilation; air scrubbing by removing NH_3 from the air through forced ventilation in combination
- Preventing emissions from slurry storage facilities mainly involves the use of solid or floating covers or allowing the formation of a natural crust.

- Low-emission slurry application techniques involve either injection or applying the slurry below the vegetation canopy, using a trailing shoe or hose, which can also achieve significant reductions and is quicker and cheaper than injection. Slurry dilution is another method to decrease emissions, often via irrigation systems. For solid manure, rapid incorporation into the soil through ploughing in reduces NH_3 emissions, however, this is only applicable for arable before sowing/planting, and not for established grassland.
- NH_3 emission from mineral fertiliser application can be reduced by opting for low-emission N fertilisers, such as ammonium nitrate, avoiding urea which is associated with much higher emissions. The most effective method, up to 90% reduction, can be through the switching from urea to ammonia nitrate. If urea is used, emissions can be reduced by using urease inhibitors. Incorporating the fertiliser into the soil and irrigating after spreading are further techniques;

The above strategies can all been described as “Category 1” methods, as they are seen as practical to the farmer and there are sufficient quantitative data to calculate emission reductions. UNECE (Bittman et al., 2014) describes the categories as follows:

- Category 1 techniques and strategies are well researched, considered to be practical or potentially practical, and there are quantitative data on their abatement efficiency, at least on the experimental scale;
- Category 2 techniques and strategies are promising, but research is at present inadequate for quantification at a practical level, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that such techniques cannot be used as part of an NH_3 abatement strategy, but may be useful depending on local circumstances;
- Category 3 techniques and strategies have not yet been shown to be effective or are likely to be excluded on practical grounds.

Costs for implementing abatement techniques ranges from a net saving of €1 per kg NH_3-N saved (for some manure spreading techniques) up to around €10 per kg NH_3-N saved for implementing air scrubbers in housing systems (Bittman et al., 2014). Such cost calculations may also be compared with environmental benefits (van Grinsven et al., 2013).

The tables below (Table 5.1.1.1 and Table 5.1.1.2) of NH_3 mitigation measures were prepared as part of Defra project AQ0834 (Dragosits et al. 2015). This is not a comprehensive list of all potential measures, but represents the most promising measures that might be realistically implemented and for which robust evidence of emission reductions exists. Data have been compiled from the most relevant and up to date sources, but insufficient information is available to fully populate the table for all measures. For example, information on costs and cost effectiveness is lacking for many of the listed measures, and costs become lower as methods are more widely adopted.

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
1	Lower crude protein diet	Formulating dairy cattle diets such that protein content does not greatly exceed requirement	Dairy cow manure management	L	Lower total N excretion; lower urinary N excretion	10 (?)	-£16.00 per animal place	Lower N excretion means subsequent N losses throughout the manure management continuum will be lower	Lower N fertiliser value of manure.
2	Increased scraping frequency	Increased frequency of removing manure from the floor of dairy cow cubicle housing	Dairy cow cubicle housing	L	Lower NH_3 flux from dairy cow cubicle house	15 (0-20)	£39.70 per animal place	Animal health/welfare benefits due to cleaner drier floors	
3	Grooved floors for dairy cow cubicle housing	Grooved floors allow faster drainage of urine to storage, lowering the potential for NH3 emission from the dairy house floor.	Dairy cow cubicle housing	M	Lower NH_3 flux from dairy cow cubicle house	35 (25-45)	?	Animal health/welfare benefits due to cleaner drier floors	
4	Washing down dairy cow collecting yards	Pressure washing (or hosing and brushing) of dairy cow collecting yards immediately following each milking event	Dairy cow collecting yards	H	Lower NH_3 flux from dairy cow collecting yard	70 (50-90)	£0.69 per animal place	N/A	Risk of run-off from yards to water courses; containment should be in place
5	Partially-slatted floors for pig housing	A 50:50 void: floor area (compared with traditional 80:20) can further reduce the fouled floor area. Also, a domed lying area will encourage any deposited urine to quickly	Pig housing	M	Lower NH_3 flux from pig house	30 (10-50)	£6.68 per animal place	Reduction in odour emissions; Higher fertiliser value of manure	

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
		drain to the below-slat storage.							
6	Frequent slurry removal from pig housing	Frequent and complete slurry removal from the below-slat pit using vacuum system	Pig housing	L	Lower NH_3 flux from pig house	25 (?)	£0 per animal place	Reduction in odour emissions; Higher fertiliser value of manure; improved in-house air quality	If greater manure N content is not taken into account, potentially greater subsequent N emissions, or N leaching/run-off
7	Floating balls on slurry surface	A layer of non-stick balls are floated on the below-slat slurry surface	Pig housing	L	Lower NH_3 flux from pig house	25 (?)	£0.85 per animal place	Same as no. 6	Same as no. 6
8	Acid scrubbers	Acid scrubbers fitted to air outlets of mechanically ventilated pig or poultry housing	Pig/poultry housing	H	Lower NH_3 flux from pig/poultry house	80 (70-90)	£10.00 for pigs; ? for poultry per animal place	Reductions in odour and PM emissions	CO_2 emissions from increased energy use

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
9	Air-drying belt-removal systems	Air drying of manure on belt-removal systems for laying hens	Laying hens housing	M	Lower NH_3 flux from laying hen house	30 (0-70)	£0.32 per animal place	Reduction in odour emissions; Higher fertiliser value of manure	CO_2 emissions from increased energy use; If greater manure N content is not taken into account, potentially greater subsequent N emissions, or N leaching/run-off
10	In-house poultry litter drying	Air drying of manure in broiler and other litter-based poultry housing systems	Litter-based poultry housing	M	Lower NH_3 flux from poultry house	30 (10-50)	£0.08 per animal place	Same as no. 9	Same as no. 9
11	Addition of aluminium sulphate to poultry litter	Regular addition of aluminium sulphate to reduce poultry litter pH	Litter-based poultry housing	M	Lower NH_3 flux from poultry house	50 (?)	?	?	?
12	Fit rigid cover to slurry tanks	A tent-like structure is fitted to above-ground slurry tanks to reduce gaseous transfer from the slurry to the atmosphere	Slurry storage	H	Lower NH_3 flux from slurry tank	80 (?)	£1.58 per tonne manure stored	Reduces amount of rainwater entering tanks directly, and thereby volume of slurry that needs handling and associated costs (fuel, staff time); reduction in odour emissions; Higher fertiliser value of manure	If greater manure N content is not taken into account, potentially greater subsequent N emissions, or N leaching/run-off

No.	Method	Description	Source	Effecti-veness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
13	Floating cover on slurry stores	Floating clay granules or similar to reduce gaseous transfer from slurry surface to the atmosphere	Slurry storage	M	Lower NH_3 flux from slurry store	50 (30-70)	£0.65 for slurry tanks; £0.85 for slurry lagoons, per tonne manure stored	N/A	If greater manure N content is not taken into account, potentially greater subsequent N emissions or N leaching/run-off; may increase N2O emissions from storage
14	Slurry bags	A large bag into which slurry is pumped for storage	Slurry storage	H	Lower NH_3 flux from slurry store	95 (?)	£4.00 per tonne manure stored	Reduces amount of rainwater entering tanks directly, and thereby volume of slurry that needs handling; reduces all gaseous emissions at storage; higher fertiliser value of manure	If greater manure N content is not taken into account, potentially greater subsequent N emissions or N leaching/run-off

No.	Method	Description	Source	Effecti-veness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
15	Sheet cover on FYM/poultry manure heap	Farm yard manure and poultry manure heaps are covered with an impermeable sheet for the duration of storage	FYM/poultry manure storage	M	Lower NH_3 flux from manure heap	60 (30-90)	£0.63 per tonne manure stored	Higher fertiliser value of manure	Potentially greater CH_4 emissions due to more anaerobic conditions; Odour emissions potentially greater at heap break-out; If greater manure N content is not taken into account, potentially greater subsequent N emissions or N leaching/run-off
16	Trailing hose slurry application	Apply slurry to land via trailing hoses (band spreading) instead of surface broadcast application	Slurry application	L	Lower NH_3 flux from slurry spreading	30 (0-50)	£0.46 per m3 of slurry applied	Reduce odour emissions; more uniform application; higher fertiliser value of manure	Possibility of greater direct in-field N_2O emissions, although these may be offset to some extent by decreased indirect N_2O emissions from lower NH_3 volatilisation/ deposition and lower overall emissions if N application rate is reduced to account for increased fertiliser value; Possibility of enhanced leaching/run-off,

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
									depending on time of application.
17	Trailing shoe slurry application	Apply slurry to land via trailing shoe instead of surface broadcast application	Slurry application	M	Lower NH_3 flux from slurry spreading	60 (20-80)	£0.59 per m3 of slurry applied	Same as no. 16	Same as no. 16
18	Shallow injection slurry application	Apply slurry to land via open-slot shallow injection instead of surface broadcast application	Slurry application	H	Lower NH_3 flux from slurry spreading	70 (50-90)	£0.69 per m3 of slurry applied	Same as no. 16	Same as no. 16; Potential dieback on grassland, particularly under hot, dry conditions
19	Deep injection slurry application	Apply slurry to land via deep closed slot injection instead of surface broadcast	Slurry application	H	Lower NH_3 flux from slurry spreading	90 (80-100)	£0.69 per m3 of slurry applied	Same as no. 16	Same as no. 16; Potential dieback on grassland, particularly under hot, dry conditions.
20	Rapid incorporation of surface-spread slurry (within 4h)	Surface applied slurry is incorporated into the soil within 4h of application by either plough, disc or tine	Slurry application	M-H	Lower NH_3 flux from slurry spreading	Plough - 65; Disc/tine - 50 (30-80)	Cattle £0.15/£0.08; Pig £0.25/£0.13 (plough/disc), per m3 of slurry applied	Same as no. 16	Same as no. 16

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
21	Rapid incorporation of surface-spread slurry (within 24h)	Surface applied slurry is incorporated into the soil within 24h of application by either plough, disc or tine	Slurry application	L	Lower NH_3 flux from slurry spreading	30 (10-50)	Cattle £0.15/£0.08; Pig £0.25/£0.13 (plough/disc), per m3 of slurry applied	Same as no. 16	Same as no. 16
22	Rapid incorporation of FYM (within 4h)	Surface applied FYM is incorporated into the soil within 4h of application by either plough, disc or tine	Manure application	M-H	Lower NH_3 flux from manure application	Plough - 70; Disc/tine - 45 (30-80)	Cattle £0.30/£0.16; Pig £0.34/£0.19 (plough/disc), per tonne of manure applied	Same as no. 16	Same as no. 16
23	Rapid incorporation of FYM (within 24h)	Surface applied FYM is incorporated into the soil within 24h of application by either plough, disc or tine	Manure application	L	Lower NH_3 flux from manure application	30 (10-50)	Cattle £0.30/£0.16; Pig £0.34/£0.19 (plough/disc), per tonne of manure applied	Same as no. 16	Same as no. 16

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
24	Rapid incorporation of poultry manure (within 4h)	Surface applied poultry manure is incorporated into the soil within 4h of application by either plough, disc or tine	Manure application	M-H	Lower NH_3 flux from manure application	Plough - 80; Disc/tine - 55 (30-90)	Layers £0.79/£0.43; Broilers £1.48/£0.80 (plough/disc), per tonne of manure applied	Same as no. 16	Same as no. 16
25	Rapid incorporation of poultry manure (within 24h)	Surface applied poultry manure is incorporated into the soil within 24h of application by either plough, disc or tine	Manure application	L	Lower NH_3 flux from manure application	30 (10-50)	Layers £0.79/£0.43; Broilers £1.48/£0.80 (plough/disc), per tonne of manure applied	Same as no. 16	Same as no. 16
26	replace urea with ammonium nitrate	Replace urea fertiliser with an equivalent quantity of ammonium nitrate fertiliser (associated with a much lower EF)	Fertiliser application	H	Lower NH_3 flux from fertiliser application	80 (?)	£0.15 per kg N applied	N/A	Same as no. 16
27	replace UAN (urea ammonium nitrate) with ammonium nitrate	Replace UAN fertiliser with an equivalent quantity of ammonium nitrate fertiliser (associated with a much lower EF)	Fertiliser application	H	Lower NH_3 flux from fertiliser application	65 (?)	£0.15 per kg N applied	N/A	Same as no. 16

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
28	Include urease inhibitor with urea fertiliser	Urease inhibitors slow the hydrolysis of urea to ammonia	Fertiliser application	H	Lower NH_3 flux from fertiliser application	70 (?)	£0.15 per kg N applied	N/A	Same as no. 16
29	Include urease inhibitor with UAN fertiliser	Urease inhibitors slow the hydrolysis of urea to ammonia	Fertiliser application	M	Lower NH_3 flux from fertiliser application	40 (?)	£0.15 per kg N applied	N/A	Same as no. 16
30	Convert intensive agricultural land (arable and grass) to unfertilised grassland or semi-natural land cover (inc. woodland) around Designated Sites	change land use from intensive agriculture to unfertilised grass or semi-natural land cover, with no fertiliser of manure applied	Manure and fertiliser application	M	Lower NH_3 flux in vicinity of Designated Sites due to removal of emissions from manure and fertiliser application	90 (?)	similar to set-aside schemes, dependent on lost income to farms compared with current practice, per hectare	converted areas could acquire amenity/conservation value of benefit to species present at the Designated site, depending on type of conversion ; reduced GHG emissions and nitrate leaching	

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
31	As above, but with extensive grazing	As above, but with extensive grazing to manage the sward	Manure and fertiliser application	M	Lower NH_3 flux in vicinity of Designated Sites due to removal of emissions from manure and fertiliser application	80 (?)	similar to set-aside schemes, dependent on lost income to farms compared with current practice	converted areas could acquire amenity/conservation value of benefit to species present at the Designated site, depending on type of conversion ; reduced GHG emissions and nitrate leaching (with good stock management at very low stocking rates)	Careful stock management to avoid poaching, run-off and nitrate leaching
32	reduce fertiliser application rates	reduce fertiliser N application rates to below the economic optimum	Fertiliser application	M	Lower NH_3 flux in vicinity of Designated Sites due to reduction of emissions from fertiliser application	20 (?)	yield reduction, depending on crop, per hectare	reduction in nitrate leaching and N_2O emissions	

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%, range)	Cost (£ per unit)	Co-benefits	Trade-offs
33	siting of temporary manure heaps away from Designated Sites	siting of temporary manure heaps in fields away from the vicinity of Designated Sites (at least 500m), also taking account of local topography and prevailing winds	Manure storage	M	Lower NH_3 flux in vicinity of Designated Sites due to greater distance from manure storage facilities	?	0		alternative locations for temporary manure storage may be less suitable from a hydrological point of view

Table 5.1.1.1: Measures to reduce direct ammonia emissions at source. Summary description, effectiveness, co-benefits and trade-offs

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
1	Blue Low effective-ness	Lower crude protein diet	100% of dairy cow winter diet (Pig and poultry diets assumed to have already adopted this approach and reflected in N excretion values decreasing over the years)	promotion of best practice, mainly suitable for larger operations	Through feed manufacturers/suppliers? Difficult for home grown/home mix operations	Ability to match diet to requirement	?	Difficulties in formulating appropriate diet from available/low cost ingredients; additional cost and time; uncertainties over composition of forage component of the diet
2	Blue Low effective-ness	Increased scraping frequency	100% of dairy cow cubicle houses	Potential future mechanism: Capital grants for automated scraping equipment (e.g. through CSF grants)	Difficult - presence of automatic scraper systems doesn't equate with their frequency of use	Quality of scraper system; wetness of excreta on cubicle house floor; the extent to which an emitting layer is left behind	?	Not necessarily easy or practical to retrofit automatic scraper systems to some existing cubicle houses; for tractor-scraped systems implies additional labour that could be employed elsewhere on the farm
3	Amber	Grooved floors for dairy cow cubicle housing	New build only	Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants)			0	New build only

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
4	Blue High effectiveness	Washing down dairy cow collecting yards	100% of dairy cow collecting yards	promotion of best practice		Operator care and attention, time spent, water pressure	?	Time/labour requirement; water use contributes to larger slurry volumes to be managed
5	Blue Medium effectiveness	Partially-slatted floors for pig housing	New build only	Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants)			?	New build only
6	Amber	Frequent slurry removal from pig housing	New build only	Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants)		Completeness of removal, frequency	?	New build only; requirement for a covered external storage pit
7	Amber Low effectiveness	Floating balls on slurry surface	100%	promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser)		Integrity of layer	0	
8	Blue High effectiveness	Acid scrubbers	New build only - very costly to retrofit	Current mechanism: permitting under IED for large installations close to designated sites Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants);	Site inspections		?	New build only

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
9	Blue Medium effectiveness	Air-drying belt-removal systems	100% of cage-kept laying hens with belt removal	Current mechanism: permitting under IED for large installations close to designated sites; promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants);	Site inspections, records of dryer running times		?	Running costs (energy)
10	Blue Medium effectiveness	In-house poultry litter drying	100% of litter-based poultry housing	Current mechanism: permitting under IED for large installations close to designated sites; promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new livestock housing (e.g. through CSF grants);	Site inspections, records of dryer running times		?	Cost of retro-fitting, running costs

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
11	Amber	Addition of aluminium sulphate to poultry litter	100% of litter-based poultry housing	Current mechanism: permitting under IED for large installations close to designated sites				?
12	Blue	Fit rigid cover to slurry tanks	100% of slurry tanks	Current mechanism: permitting under IED for large installations close to designated sites; promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure storage facilities (e.g. through CSF grants);	Site inspections, aerial observations	Integrity of the cover;	0% cattle slurry; 18% pig slurry	Some existing tanks have insufficient structural support; perceived issues with filling/emptying

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
13	Amber	Floating cover on slurry stores	100% of slurry stores	Current mechanism: permitting under IED for large installations close to designated sites; promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure storage facilities (e.g. through CSF grants);	Site inspections, aerial observations	Integrity of the cover;	80% cattle stores assumed to be crusted; 18% pig slurry stores covered	Wind drift may compromise cover; may be difficult to manage; perceived filling/emptying problems
14	Amber	Slurry bags	100% of slurry storage	Current mechanism: permitting under IED for large installations close to designated sites; promotion of best practice and savings achievable due to retaining N content in slurry to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure storage facilities (e.g. through CSF grants);	Site inspections, aerial observations	Cleanliness of operation	0%	Relatively new practice; fear of spillages; perceived difficulties in filling/emptying

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
15	Amber	Sheet cover on FYM/poultry manure heap	100% of FYM/poultry manure storage	promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Site inspections, aerial observations	Integrity of cover	0%	Large quantities of dirty plastic to manage; practical difficulties in covering heaps; Not suitable for heaps which are added to frequently
16	Blue	Trailing hose slurry application	100% of slurry to arable land	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure spreading equipment (e.g. through CSF grants);	Difficult: Contractor receipts, machine purchase?	Slurry and soil characteristics (does slurry remain in narrow bands); More effective when applied to a growing arable crop with some canopy cover	3% cattle; 19% pig	Slower operation

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
17	Blue	Trailing shoe slurry application	100% of slurry to grassland	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure spreading equipment (e.g. through CSF grants);	Difficult: Contractor receipts, machine purchase ?	Slurry and soil characteristics (does slurry remain in narrow bands); more effective with greater sward cover	0%	Slower operation
18	Blue	Shallow injection slurry application	c. 70% of grassland area; arable prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure spreading equipment (e.g. through CSF grants);	Difficult: Contractor receipts, machine purchase ?	Application rate; slurry and soil characteristics;	1% Cattle; 11% pig	Greater power requirement; potential for sward damage; slower operation;

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
19	Blue	Deep injection slurry application	c. 70% of grassland area; arable prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser) Potential future mechanism: Capital grants for new manure spreading equipment (e.g. through CSF grants);	Difficult: Contractor receipts, machine purchase ?	Soil characteristics; application rate	0%	Greater power requirement; potential for sward damage; slower operation;
20	Amber Difficult to verify	Rapid incorporation of surface-spread slurry (within 4h)	Slurry applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Difficult	Soil and weather conditions - degree of manure burial	6% of slurry applied to arable land	Opportunity costs of labour/equipment
21	Pink Most NH_3 is volatilised within 24 hours	Rapid incorporation of surface-spread slurry (within 24h)	Slurry applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Difficult	Soil and weather conditions - degree of manure burial	19% of slurry applied to arable land	Opportunity costs of labour/equipment

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
22	Amber Difficult to verify	Rapid incorporation of FYM (within 4h)	FYM applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Difficult	Soil and weather conditions - degree of manure burial	3% of FYM applied to arable land	Opportunity costs of labour/equipment
23	Pink Most NH_3 is volatilised within 24 hours	Rapid incorporation of FYM (within 24h)	FYM applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Difficult	Soil and weather conditions - degree of manure burial	18% of cattle and 26% of pig FYM applied to arable land	Opportunity costs of labour/equipment
24	Amber Difficult to verify	Rapid incorporation of poultry manure (within 4h)	Poultry manure applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced requirement for mineral fertiliser)	Difficult	Soil and weather conditions - degree of manure burial	8% of poultry manure applied to arable land	Opportunity costs of labour/equipment
25	Pink Most NH_3 is volatilised within 24 hours	Rapid incorporation of poultry manure (within 24h)	Poultry manure applied to arable land prior to crop establishment	Current mechanism: promotion of best practice and savings achievable due to retaining N content in manure to be used as fertiliser (reduced	Difficult	Soil and weather conditions - degree of manure burial	46% of poultry manure applied to arable land	Opportunity costs of labour/equipment

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
				requirement for mineral fertiliser)				
26	Blue	replace urea with ammonium nitrate	All urea fertiliser	Potential future mechanism: tax intervention to make the lower emission fertiliser cheaper	Through fertiliser manufacturers/distributers	Soil and weather conditions	0%	
27	Blue	replace UAN (urea ammonium nitrate) with ammonium nitrate	All UAN fertiliser	Potential future mechanism: tax intervention to make the lower emission fertiliser cheaper	Through fertiliser manufacturers/distributers	Soil and weather conditions	0%	
28	Blue	Include urease inhibitor with urea fertiliser	All urea fertiliser	Potential future mechanism: regulation	Through fertiliser manufacturers/distributers	Soil and weather conditions	0%	
29	Blue	Include urease inhibitor with UAN fertiliser	All UAN fertiliser	Potential future mechanism: regulation	Through fertiliser manufacturers/distributers	Soil and weather conditions	0%	

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
30	Blue	Convert intensive agricultural land (arable and grass) to unfertilised grassland or semi-natural land cover (inc. woodland) around Designated Sites	All intensively farmed fields within buffer zones around sensitive Designated Sites, prioritised to fields immediately adjoining sites, with wider buffer zones upwind of the prevailing local conditions, up to 500m	Potential future mechanism: Create and promote agri-environment stewardship scheme options for ammonia in target areas near designated sites	Site inspections, aerial observations	highly dependent on current land use and management practice	?	potentially large economic impact to farm business, would need suitable incentives;

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current impleme-ntation (% of sector)	Barriers to uptake
31	Blue	Convert intensive agricultural land (arable and grass) to unfertilised grassland or semi-natural land cover (Inc. woodland) around Designated Sites, with extensive grazing	All intensively farmed fields within buffer zones around sensitive Designated Sites, prioritised to fields immediately adjoining sites, with wider buffer zones upwind of the prevailing local conditions, up to 500m	Potential future mechanism: Create and promote agri-environment stewardship scheme options for ammonia in target areas near designated sites	Site inspections, aerial observations	highly dependent on current land use and management practice; stocking density to be permitted	?	potentially large economic impact to farm business, would need suitable incentives;
32	Blue	Reduce fertiliser application rates	All fertilised agricultural land	Potential future mechanism: Create and promote agri-environment stewardship scheme options for ammonia in target areas near designated sites	Site inspections (soil samples?) - difficult/sampling expensive	20 % reduction in N fertiliser below the economic optimum would typically reduce crop yields by 2-10%	?	would need suitable incentives due to economic impact to farm business

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/ enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
33	Blue Possibly even further than 500 m	Siting of temporary manure heaps away from Designated Sites	All farmland	Potential future mechanism: regulation	Site inspection	local conditions/landscape	?	Convenience/transport costs to the farmer (distances to locations of manure origin and manure spreading); May also depend on farm size/distance of a farm's fields from the Designated Site, i.e. all fields of a small farm may be located close to a Designated Site - measure could still be partially effective through finding a suitable location as far as possible from the Site.

Table 5.1.1.2: Summary of measures to reduce emissions at source, factors governing potential implementation

Colour Key:

- Blue = well tested at multiple sites with outcomes consistent with accepted logic chain. No reasonable dis-benefits or practical limitations relating to successful implementation.
- Amber = agreement in the expert community there is an intervention logic chain which can be supported but either evidence is currently limited and/or there are some trade-offs or dis-benefits which WG need to consider.
- Pink = either expert judgement does not support logic chain and/or whilst logic chain would suggest it should work there is evidence of one or more of the following:
  - its practical potential is limited due to a range of issues (e.g. beyond reasonable expectation of advisory support which can be supplied and/or highly variable outcome beyond current understanding or ability to target),
  - the outcome/benefit is so small in magnitude with few co-benefits that it may not be worth the administration costs,
  - there are significant trade-offs.

5.1.2 Causality

How good is the evidence for causality and attribution?

- Blue = well tested at multiple sites with outcomes consistent with accepted logic chain;
- Amber = agreement in the expert community there is an intervention logic chain which can be supported but evidence is currently limited;
- Pink = either expert judgement does not support logic chain and/or whilst logic chain would suggest it should work there is evidence that its practical potential is limited due to a range of issues (e.g. sensitivity to implementation which radically affects outcome beyond reasonable expectation of advisory support which can be supplied).

The Blue/Amber/Pink scores are provided for each measure Table 5.1.1.2.

Although all these measures are considered Category 1, i.e. they have been demonstrated to be effective, some are relatively new techniques and not all have been taken up to a large extent in the UK. The colour coding reflect these issues, as well as the overall effectiveness of the measure. In some cases, the colour coding score is given as Blue, but the effectiveness of the measure is also highlighted (Low, Med or High). 7.1 at the end of this document gives an overview of the colour coding for the main groups of measures.

5.1.3 Co-benefits and trade-offs

Co-benefits and trade-offs for each individual measure are highlighted in Table 5.1.1.2. The following text summarises some of the main issues.

Reducing crude protein in housed cattle diets can mainly be achieved by switching from grass to maize silage. However, maize silage is a crop that can be susceptible to elevated runoff and soil erosion compared with grass, so incurs potential trade-offs earlier in the supply chain. The suitability of land for maize production is clearly limited by slope in Wales, and replacing grass with arable will also result in soil C losses.

Covering slurry stores is effective, *per se*, but this is a relatively small emission source in Wales. A key economic benefit is the reduced spreading costs as a result of excluding rainwater from stores, thereby reducing staff and fuel costs. There are potential trade-offs with some measures of manure storage which could increase GHG emissions of N_2O and CH_4.

Reducing ammonia emissions from livestock housing, manure storage and land spreading means that more N is available from manure to promote plant growth. Hence, if timing and doses are appropriate for plant growth stages, productivity should be higher with lower losses to the environment, and imports of additional N to the farm, mainly manufactured mineral N, could be reduced, thereby potentially providing cost savings. However, this also means that the potential losses during manure application may be greater if the higher N content of the manure is not taken into account.

5.1.4 Magnitude

The efficiency of each measure is provided in Table 5.1.1.1. Efficiencies of measures to reduce NH_3 emissions at source vary from 10 – 95%. The most effective measures are acid scrubbers within animal units, slurry bags or rigid covers on slurry tanks for storage, slurry injection methods for manure application, and replacement of urea based fertiliser with ammonium nitrate (NH_4NO_3) fertiliser, or use of urease inhibitors where that is not feasible.

Overall, slurry storage is generally the smallest term in the ammonia emissions inventory for slurry-based livestock systems. Therefore reducing losses from land spreading is much more effective than covering slurry stores. However, more nutrient nitrogen is retained in covered slurry stores, thereby increasing the potential for further cost savings at the farm scale, especially for larger cattle farms. This is in addition to cost savings to farmers from avoiding dilution through rainfall and associated additional staff and fuel costs for spreading, especially in an area with high rainfall such as Wales.

Some measures, such as ploughing in surface applications of FYM within 24 hours are not considered effective as a substantial component of the NH_3 is volatilised within this period. Ploughing in should be conducted within 4 hours to minimise such losses. However, this is difficult to verify and often operationally difficult to achieve (see Section 5.1.10).

5.1.5 Timescale

All measures are potentially achievable within a 0-5 year timeframe, if sufficient funding is available. The exceptions are measures such as slatted or grooved floors in animal houses with solid flooring, or acid scrubbers in pig or poultry units which are only considered practical with new-build installations. Uptake of these measures will depend on the incentives provided to replace existing installations, and/or the life expectancy of existing installations.

5.1.6 Spatial issues

The majority of these measures are focused on reducing emissions at source. However some of these have a clear spatial component at local scale. For example, measures 30 & 31 relate to reducing emissions through land use change around protected areas, i.e. replacing intensive agriculture which produces high NH_3 emissions with less intensive land use such as woodland or low intensity grazing land. At a local scale, location of temporary manure heaps can also help reduce immediate pressure on sensitive habitats. Initial guidance recommends these be sited at least 500 m from sensitive habitats, although some studies suggest that NH_3 transport from local sources is likely to extend further, including upwind of the prevailing winds (Jones et al. 2013), so distances >500 m are preferable.

At a broader landscape to national scale there are clear spatial issues. These hinge on policy direction as to whether to try and maintain habitats and protected areas which are in good condition with high biodiversity in ‘good air quality’ areas, or to try and reduce emissions and deposition in areas which are already impacted. This is a complex issue, discussed in more detail in section 5.2.5, and is of increasing policy interest. However, discussions on this issue are still relatively young and it would benefit from a wider debate.

5.1.7 Displacement

Displacement issues may exist with respect to manure management, and transport of manures between farms. Reducing ammonia emissions from solid manure (or farmyard manure, FYM) is much more constrained than for slurry management, for farm management/operational reasons. Most farms in Wales are specialist sheep farms and for their, relatively short, housing period sheep are managed to produce FYM. The only practical and effective method is rapid incorporation of FYM into arable soil, but this is not applicable to grassland and specialist sheep farms generally have very little arable land. This may lead to displacement issues. There are large numbers of poultry farms clustered in some parts of Wales, and there is evidence of waste movements between local farmers,

5.1.8 Longevity

The majority of these measures have good longevity because they require investment in infrastructure. However, this also comes with disadvantages where take up of new technology may be slow due to previous investment in expensive infrastructure.

5.1.9 Climate interactions

Interactions with climate are not well studied. However, warmer temperatures are expected to lead to greater loss rates through volatilisation from manures and fertiliser (e.g. Sutton et al. 2013, Riddick et al. 2017). Greater intensity rainfall may lead to increased risk of surface runoff of manure or fertiliser into aquatic systems, and greater losses into groundwater due to enhanced leaching.

5.1.10 Social and economic barriers

Factors influencing take up for each measure are provided in Table 5.1.1.2. Many of these are cost based, either due to high capital costs of installation, or increased labour or energy costs to implement the measures in the longer term. Some measures are only practicable for new build installations. Some measures still carry uncertainty in how best to practically manage on a day-to-day basis, such as formulating reduced protein diets.

5.1.11 Metrics and verification

Suggested ways of monitoring or verifying implementation for each measure are provided in Table 5.1.1.2.

5.2 Woodland planting and vegetation management to remove pollutants from the atmosphere

This section focuses primarily on the benefits from woodland, although all UK vegetation types remove pollutants.

Background

What makes trees particularly effective scavengers of air pollutants is their effect on turbulence and a large surface area (Beckett et al 2000, Nowak 2000). Having a higher roughness length (and lower aerodynamic resistance R_a) aids mechanical turbulence and promotes dry deposition to the surface. Dry deposition rates to trees exceed those to grassland by typically a factor of 3–20 (Gallagher et al., 2002, Fowler et al., 2004). This implies that the conversion of grassland and arable land to trees or targeted management of existing wooded areas can be used to promote the removal of ammonia from the atmosphere.

Several previous studies have shown the effectiveness of trees in capturing pollutants. Many studies have focused on particulates (e.g. $PM_{10}/_{2.5}$) in relation to improving urban air quality. For example Nowak *et al.* (2013) modelled $PM_{2.5}$ removal by trees in ten US cities and associated health effects. McDonald *et al.*, (2007) modelled the potential of urban tree planting to mitigate PM_{10} across two UK conurbations. Novak et al. (2006), used meteorological and air pollution data to show the removal of O_3, PM_{10}, NO_2, SO_2, CO by urban trees and shrubs across the United States. Some studies have looked at the suitability and pollutant capture efficiency of particular trees. For example, Becket et al. (2001) showed in wind tunnel experiments that coniferous species, and broadleaf trees with hairy leaves, had a greater effectiveness at capturing particles than other broadleaf trees.

In the UK, work to develop Natural Capital Accounts for air pollution removal by vegetation has shown the substantial health benefits from woodland in the UK landscape due to its capacity to remove a wide range of pollutants (Jones et al. 2017). The report calculates the health benefits of UK vegetation in its entirety of £1 billion per year. Trees remove a wide range of pollutants which have health impacts, including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O3. Roughly 75% of that health benefit comes from the removal of $PM_{2.5}$ by trees, as $PM_{2.5}$ is responsible for the majority of the health impact, and woodland is particularly efficient at removing $PM_{2.5}$ from the air.

In the agricultural landscape, similar studies examining the usefulness of trees to capture ammonia are limited. The capture of ammonia by surrounding vegetation has been studied by Patterson et al. (2008a), who observed lower NH_3 concentrations when potted trees were present downwind of poultry house fans compared with when the trees were removed (16.4 versus 19.3 ppm). Further work by Patterson et al. (2008b) also showed that the foliar N concentrations of Spike hybrid poplar and Norway spruce were greater near the exhaust fans compared to control plants at 40m or more. Spike hybrid poplar was found to retain greater foliage N than Norway spruce. Both species were able to capture NH_3 near the housing's fans.

The key processes by which trees can have a beneficial effect as landscape structures to mitigate NH_3 air pollution can be summarised as follows:

1. To reduce emissions from slurry lagoons by reducing the wind speed over its surface;
2. To recapture and dilute emissions from sources upwind of the trees through increased turbulence and deposition velocities;
3. To increase the dispersion above the canopy through increased mixing thereby reducing deposition to nearby sensitive habitats.

As the plume from the source approaches the tree-belt, part of the plume is pushed upwards and does not impact with the tree-belt itself. Instead, it flows over the top where turbulence is increased leading to additional dry deposition. As the rest of the plume enters the tree belt the air flow (wind speed) is reduced and NH_3 capture occurs.

When considering emissions of NH_3, reactions in the atmosphere to ammonium NH_4^+ should also be taken into account, in other words how much of the emitted NH_3

is deposited as wet or dry NH_4^+. For receptors close to sources (e.g. <1 km) dry deposition is driven by the gaseous form (NH_3), as conversion to NH_4^+ has not yet had time to occur. Furthermore, the dry deposition velocity of NH_3 is about five times higher than for particulate NH_4^+ (Ferm, 1998).

Table 5.2.1 below summarises the effectiveness of woodland to remove ammonia or other pollutants from the atmosphere, either from local sources or pollutants emitted further afield. The text also discusses considerations related to planting of trees in the wider landscape.

No.	Method	Description	Source	Effectiveness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%)	Cost (£ per unit)	Co-benefits	Trade-offs
34	Tree belt next to livestock house	Plant tree belt next to livestock house, especially effective if the Designated site is downwind (of prevailing direction) from livestock house (N.B. dimensions of tree belt need to be substantially larger than housing)	Poultry or pig houses, cattle sheds, slurry stores	M	Lower concentrations of ammonia on far side of woodland, increased deposition to woodland	20 (5-50)	£2.50-£5, per kg NH_3 recaptured	Woodland ecology; carbon capture; wood crop; animal welfare status; reduced wet deposition of N; reduction of PM	potential for increased N_2O emissions (limited evidence for this); potential nitrate leaching; potential interference with water balance of wetland habitats in the immediate vicinity of the tree belts
35	Tree belt next to Designated Site	Plant tree belt next to Designated Site, especially effective if the Designated site is downwind (of prevailing direction) from livestock house (N.B. dimensions of tree belt need to be substantially larger than housing)	Poultry or pig houses, cattle sheds, slurry stores	M	Lower concentrations of ammonia on far side of woodland, increased deposition to woodland	20 (5-50)	£2.50-£5, per kg NH_3 recaptured	Same as no. 34	Same as no. 34

No.	Method	Description	Source	Effecti-veness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%)	Cost (£ per unit)	Co-benefits	Trade-offs
36	Tree belt upwind and downwind of slurry storage	Tree belt shelters air flow across the lagoon and also re-captures ammonia downwind of the slurry store (note modelling included the increase in T associated with the sheltering of the slurry	Slurry storage	M	Lower concentrations of ammonia on far side of woodland	20 (10-30)	£2.50-£5, per kg NH_3 recaptured	Same as no. 34	Same as no. 34
37	Keeping free range livestock under trees with short backstop tree belt	Making a silvopastoral area in which the livestock (most suitable for poultry but could be applicable to other species). Emissions are mostly recaptured within the woodland canopy rather than released to the atmosphere	Livestock (poultry, pig)	M	Lower concentrations of ammonia on far side of woodland	45 (20-60)	-£8.50, per kg NH_3 recaptured	Same as no. 34	Same as no. 34
38	New woodland planting to improve air quality	Planting woodland at landscape scale to capture air pollution, reducing pollutant concentrations	All sources	L	Lower concentrations of air pollutants on downwind side of woodland, increased dry deposition to woodland	1 – 10 (may be greater locally)		Depending on species planted and location: Improved biodiversity, recreation opportunities, noise mitigation, reduced runoff, carbon	Depending on species planted and location: allergens from pollen, emission of Biogenic Volatile Organic Compounds

No.	Method	Description	Source	Effecti-veness (Low, Med, High)	Measurement of mitigation	Mitigation effect (%)	Cost (£ per unit)	Co-benefits	Trade-offs
								sequestration, health and wellbeing of nearby population	

Table 2.2.1 Measures to capture pollutants by woodland planting. Summary description, effectiveness, co-benefits and trade-offs.

No.	Confidence	Method	Applicability (% of sector)	Existing or potential future delivery mechanisms	Verifiable/enforceable	Factors influencing effectiveness	Current implementation (% of sector)	Barriers to uptake
34	Amber	Tree belt next to livestock house	Where space allows; land cost very high if replacing useable agricultural land, though silvo-pastoral options should be considered	compatible with woodland grant schemes; potential future mechanism: ammonia options for promoting tree belts of appropriate design in suitable locations near livestock buildings	Ambient measurements at receptor site; Site inspections, aerial observations	Tree type, tree belt height, width and depth	Minor, coincident with other tree planting, e.g. in woodland free range poultry programmes	Space; cost of planting and effort of maintaining shelterbelt at maximum effectiveness
35	Blue	Tree belt next to Designated Site	Where farm space allows; land cost very high if replacing useable agricultural land though silvo-pastoral options should be considered	compatible with woodland grant schemes; potential future mechanism: ammonia options for promoting tree belts of appropriate design in suitable locations near designated sites	Ambient measurements at receptor site; Site inspections, aerial observations	Tree type, tree belt height, width and depth; in areas with a large number of diffuse emission sources tree belts around receptors are more effective than tree belts around emission sources	Minor, coincident with other tree planting	Space; cost of planting and effort of maintaining shelterbelt at maximum effectiveness
36	Amber	Tree belt upwind and downwind of slurry storage	Where farm space allows; land cost very high if replacing useable agricultural land though silvo-pastoral options should be considered	compatible with woodland grant schemes; potential future mechanism: ammonia options for promoting tree belts of appropriate design in suitable locations near slurry stores	Ambient measurements at receptor site; Site inspections, aerial observations	Tree type, tree belt height, width and depth	unknown but probably low	Space; land use pressure

37	Amber	Keeping free range livestock under trees with short backstop tree belt	Where farm space allows; land cost very high if replacing useable agricultural land though silvo-pastoral options should be considered	compatible with woodland grant schemes and certified schemes (e.g. woodland egg production); potential future mechanism: ammonia options for promoting tree belts of appropriate design in suitable locations for free-range poultry farms	Ambient measurements at receptor site; Site inspections, aerial observations	Tree type, tree belt height, width and depth	unknown but probably low	Space; land use pressure
38	Amber	New woodland planting to improve air quality	Woodland planting constrained by many factors	Small grants available	Ambient measurements, national modelling for interventions at scale	Tree type, area planted; Pollutant concentrations;	N/A	Space; land use pressure

Table 5.2.2: Summary of measures to capture pollutants by woodland planting, factors governing potential implementation

5.2.1 Causality

Blue/Amber/Pink scores for each measure for air pollution capture by woodland are shown in Table 5.2.2**.** above. Overall, the majority of these measures are Blue/Amber, summarised in 7.1 at the end of this document. The mechanistic understanding of pollution removal by trees is strong, and broadly consistent. However, the magnitude of pollution removal could be lower depending on the design of the tree belt and the time for canopy maturity and ongoing management of the tree belt to maximise functioning for ammonia mitigation. It is likely that co-benefits may be large but systematic studies have not been done (discussed in section 5.2.2 below). There are issues of scale, and location that should also be considered (discussed in section 5.2.5).

5.2.2 Co-benefits and trade-offs

Trees provide multiple co-benefits, in addition to pollution removal. Co-benefits and trade-offs for each measure are provided in Table 5.2.1 above. Carbon sequestration by trees provides both social and environmental benefits by contributing to reducing global warming. Woodlands are a major focus for recreation (Bateman et al. 2011), they reduce the health impacts of high road and rail noise (eftec et al. 2018), in urban areas they can reduce urban heat island effects and health effects associated with heatwaves (eftec et al. 2017), and they support biodiversity. There is also increasing evidence of their indirect benefit to people's wellbeing through promotion of physical activity, stress recovery, cognitive restoration and social connectedness (Hartig et al, 2014). They improve infiltration in urban areas and can contribute to reduced surface run-off, and they can reduce water quality impacts from eutrophication by shading water courses and reducing algal growth (Bachiller-Jareno et al 2019).

Planting trees around hot-spots of ammonia, together with the silvo-pastoral practice of grazing livestock under trees provide a number of benefits in the rural landscape e.g.

- Improved animal welfare using silvo-pastoral systems. Sheltering of livestock by trees provides protection from predators, the sun in hot weather (reducing heat stress) and from rain and wind during inclement weather. Productivity can be improved and mortality reduced.
- Visibility impacts can be improved as trees can break up the geometric shape of a building or hide them completely.
- Enhanced woodland biodiversity by linking up fractured areas of woodland and linking bio-corridors to maintaining the viability of agricultural woodlands and forests, preserving them for future generations, where they could act as a pool for genetic diversity in the landscape if local species are planted.
- Reducing nitrogen deposition to nearby semi-natural habitats will lower critical load/level exceedance to the network of protected nature sites.
- The potential for producing a price premium for pig and poultry produce e.g. woodland chickens or woodland pork.

Trees also have a range of dis-services. These include dropping leaves and seeds in urban areas, unwanted shading of buildings, tree root damage to pavements, roads and drainage infrastructure. The production of pollen can exacerbate asthma and hay fever, with some species being particularly allergenic. Many species emit terpenes and other Biogenic Volatile Organic Compounds which are a precursor for ozone formation and so can exacerbate tropospheric ozone concentrations, and the associated health impacts.

There are trade-offs in considering location of woodland, with different locations being optimal for different benefits (discussed in section 5.2.5). When considering where to plant woodlands, there are also trade-offs in considering what land use woodlands should replace and the loss in the benefits or services provided by the existing land use (also discussed in section 5.2.5).

Further trade-offs arise when considering tree planting to reduce adverse N deposition effects on ecosystems, where a key issue is pollution swapping. This arises when scavenging of N by the tree canopy leads to increased N input to water courses or groundwater via leaching. This is most likely for trees planted close to point sources, where conditions of N saturation of the soil system, and subsequent release of N into water courses, should be monitored. The potential for adverse impacts adjacent to sensitive ecosystems are two-fold. N transfer to surface waters or groundwater may affect sensitive wetlands (Camargo & Alonso 2006; Rhymes et al. 2015). Increased water use by trees may also lower water tables where trees are planted in large numbers, or too close to wetland sites. They may also act as a seed source of propagules to colonise protected sites.

5.2.3 Magnitude

The magnitude of pollution removal is shown for each measure in Table 5.2.1. A developing literature is quantifying and valuing the amount of ‘pollutant removal’ service provided by vegetation. Studies in the USA have shown a high economic value (Nowak et al. 2006, 2013), in the UK (Tiwary et al. 2009). However, there is some controversy over the real magnitude of benefit provided (Whitlow et al. 2014). Most studies only show a 1% reduction in pollutant concentrations by vegetation (Nowak et al. 2013). Recent modelling for the UK Natural Capital Accounts took a different modelling approach and calculated an average reduction of 10% in $PM_{2.5}$ concentrations from all UK vegetation, with an approximate annual benefit of £1 billion (Jones et al. 2017). Woodland removal of $PM_{2.5}$ pollution accounts for around 75% of the total calculated UK health benefit. Woodland planting at smaller scales will have a much smaller effect however, although at the scale of national planning for woodland creation within Wales, there is scope to realise health benefits of a reasonable magnitude. Spatial issues around where to plant woodland are discussed in section 5.2.5.

Bealey et al., 2014 have quantified the emission abatement of agricultural ammonia that is achievable with a range of different farm woodland tree systems. These range from a 20% reduction in on-farm ammonia emissions by planting trees downwind of a housing installation, to 45% reduction for placing livestock under the trees themselves.

5.2.4 Timescale

New woodland takes many years to grow to a sufficient size to provide an effective service of pollution removal. For typical conifer plantation species this is around 40 years, while for hardwoods it may be 80+ years. It takes time to develop a sufficiently large canopy with a high leaf area index per unit ground surface.

5.2.5 Spatial issues

Key spatial issues in considering woodland planting include: size of woodland and where to plant it to achieve maximum benefit.

In general, the larger the area of woodland the more pollution is removed. At small scale there are edge effects, with greater turbulence at woodland edges which leads to more efficient pollution removal. However, to achieve reductions in pollution concentrations, large areas of woodland are needed. Modelling studies suggest that the amount of pollution removed by woodland increases more-or-less linearly with increasing woodland area. To reduce pollution concentrations in ambient air masses rather than near point sources requires large areas of woodland and careful consideration of planting location.

There is some evidence that at small scale, urban street trees can exacerbate pollution problems, by reducing vertical mixing of air in street canyons, effectively trapping pollutants below the tree canopy and increasing the exposure of pedestrians and vehicle users (Gromke et al. 2008).

Location of planting is important as there may be different considerations for impacts on ecosystems and those on human health. In order to minimise ecosystem impacts, there are some divergent views. One option is to focus on areas which are most impacted, thereby reducing the magnitude of damage to the ecosystem. However, impacted systems hold a large reservoir of accumulated N in soils and plant material, which turns over very slowly and persists in the ecosystem for many decades (Rowe et al. 2017; Stevens 2016). Another option, gaining increasing traction, is to protect areas which have not yet been impacted. This has considerable advantages, since the damage per unit of N deposited is much greater at low levels of N deposition when ecosystems are still largely unimpacted, than the additional damage caused once ecosystems have already received large loads of atmospheric N (Jones et al. 2018).

For minimising human health impacts, planting woodland upwind of large populations is likely to achieve the greatest health benefit. However, this may not be as simple as considering prevailing wind directions. It is more appropriate to consider the combination of wind direction and other pollutant sources. Modelling has shown that air parcel trajectories have a considerable influence on the pollution climate and the greatest health impacts over Wales may come from the relatively small duration of time that winds blow from the East, bringing polluted air from the continent and large industrial areas in England (Harrison et al. 2012). Therefore to provide maximum benefit to urban areas, woodland should be planted taking into consideration the likely dominant pollution sources from Easterly directions, rather than in the direction of the prevailing wind.

Consideration of recreation and other services may lead to different planting patterns at a national scale (e.g. Bateman et al. 2011). Therefore, it is suggested that landscape planning should consider multiple potential outcomes which are wider than, but include, the primary aim of improving air quality.

For both environmental and human health effects, woodland planting location can be focused around point sources, thereby reducing to a small extent the emissions from that source. This will benefit all potential end-points.

For capturing ammonia emissions in the agricultural landscape tree shelter-belts can be planted downwind of livestock buildings to help reduce concentrations on the leeward side. This can be beneficial if a protected site or sensitive habitat is downwind of a livestock building. Getting the tree design structure and location of the tree belt systems in relation to the source is paramount to achieving optimal recapture. Three key elements are important for achieving optimal recapture – i) the addition of a backstop to prevent ammonia going straight through the canopy; and ii) planting trees on the prevailing downwind side of the source (although trees can be planted upwind too) and iii) the understorey at the front of the tree belt should be open enough so that the plume is directed into the denser part of the canopy. The tree belt should be more than just a few rows of trees but much deeper (e.g. 20/30/50 metres deep). Obstacles like roads or barns could restrict optimal location for siting a tree belt.

5.2.6 Displacement

Displacement issues related to woodland planting specifically for pollutant capture at local scale are likely to be minimal. At a landscape scale, this would need to consider what land is used for planting woodland.

5.2.7 Longevity

Trees take time to mature, and therefore their effectiveness at removing NH_3 or other pollutants will take some time to reach full potential. Timescales will vary by tree species, but can be considered to be at least 40 years for the majority of species to reach full capturing potential. However, effects will start to happen as the tree develops in height and canopy structure – around the 5-10 year mark – while the establishment phase of tree growth (up to 5 years) will have minimal capture efficiency. Although trees can be quickly felled, in practice woodland planting is a relatively long-lived intervention. However, where trees are planted for commercial production, the felling and replanting cycle should be taken into account when calculating long-term benefits to air quality.

5.2.8 Climate interactions

Climate risks will vary by tree species. Some species such as beech are particularly sensitive to drought (Mountford and Peterken, 2003), although beech is not widespread in Wales. Summer drought reduces tree growth increment in susceptible species such as spruce and hemlock (Dănescu et al., 2018). Drought exacerbates abiotic stress, which can lead to secondary impacts such as tree pathogens, leaf defoliators and bark beetle in a range of species (Thomas et al., 2002; Ramsfield et al., 2016; Seidl et al., 2017). Choice of tree species for new planting should consider future proofing for climate and associated risks.

5.2.9 Social and economic barriers

Potential barriers to uptake for each measure are provided in **Table 5.2.2**. These relate primarily to pressure for land, the opportunity cost of reducing or losing production from land planted with trees, the potential reduction in land value once trees have been planted versus arable land, and the costs of tree planting and ongoing maintenance.

5.2.10 Metrics and verification

Suggested monitoring options are provided for each measure in **Table 5.2.2**. These consist primarily of measurements of atmospheric pollution concentrations within or up- and down-wind of woodland. Assessment of the potential for large-scale plantings to remove pollutants from diffuse or background sources can only realistically be achieved using a range of modelling techniques, ideally using atmospheric dispersion models.

6 Evidence Gaps

Identified evidence gaps include:

i. The relative importance of protecting sensitive habitats which still show high biodiversity and are not yet severely impacted by poor air quality, compared with reducing impact at sites already showing damage from air pollution.

ii. Modelling studies to understand which woodland planting locations in Wales will provide the most benefit (both for health outcomes, and a wider suite of benefits). Planning optimum locations for woodland planting is not intuitive, and will achieve different benefits depending on location. The short- to long-distance transport of air pollutants means that this requires scenario analysis at national scale.

iii. Additional primary research on nitrogen sensitivity of habitats for which there is little or no current empirical evidence in the UK (e.g. Fens, Shingle).

iv. Improved understanding of the overall nitrogen balance in agro-forestry/silvo-pastoral systems from the canopy to the soils. This includes more measurements in and around livestock farms, and a need to better understand ammonia capture by different stages of tree growth

v. More research is needed on the timescales and chemical controls governing conversion of ammonia to ammonium aerosol formation as a component of $PM_{2.5}$.

7 Summary

Confidence	Intervention name	Key Outcomes	Key Benefits	Critical concerns
Blue	Reduction in Fertiliser application (26-29, 32)	*Reduced NH3 emissions*	*improved air quality; reduced impacts on biodiversity; reduced aquatic pollution*	
Blue	Conversion of intensive to extensive land use (30-31)	Reduced NH3 emissions	*improved air quality; reduced impacts on biodiversity; reduced aquatic pollution*	
Mostly Blue	Cattle, pig and poultry manure management at source (1-11)	Reduced NH3 emissions	*improved air quality; reduced impacts on biodiversity; reduced aquatic pollution*	
Mostly Amber	Manure storage (12-15, 33)	Reduced NH3 emissions	*improved air quality; reduced impacts on biodiversity; reduced aquatic pollution*	Potential for some increases in GHG
Mostly Amber	Woodland planting to reduce NH3 and other pollutants (34-38)	Reduced concentrations of NH3 and other pollutants	*Improved air quality; reduced impacts on biodiversity*	Some potential for pollution swapping (e.g. leaching to freshwaters)
Mix of Blue, Amber, Pink	Manure spreading (16-25)	Reduced NH3 emissions	*improved air quality; reduced impacts on biodiversity; reduced aquatic pollution*	Depends on measures. Some may not be effective in reality

Table 7.1. Summary of confidence scoring for measures.

Colour Key:

- Blue = well tested at multiple sites with outcomes consistent with accepted logic chain. No reasonable dis-benefits or practical limitations relating to successful implementation.
- Amber = agreement in the expert community there is an intervention logic chain which can be supported but either evidence is currently limited and/or there are some trade-offs or dis-benefits which WG need to consider.
- Pink = either expert judgement does not support logic chain and/or whilst logic chain would suggest it should work there is evidence of one or more of the following:
    - its practical potential is limited due to a range of issues (e.g. beyond reasonable expectation of advisory support which can be supplied and/or highly variable outcome beyond current understanding or ability to target),
    - the outcome/benefit is so small in magnitude with few co-benefits that it may not be worth the administration costs,
    - there are significant trade-offs.

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