Qualitative Impact Assessment of Land Management Interventions on Ecosystem Services ("QEIA")

Report-3 Theme-1: Air Quality

UK Centre for Ecology & Hydrology

Institute for European Environmental Policy

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Qualitative impact assessment of land management interventions on Ecosystem Services

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Siriwardena, G.M. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5D: Biodiversity - Integrated System-Based Actions (Defra ECM_62324/UKCEH 08044)

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A list of all references used in the reports is also available as a separate database.

Foreword

The focus of this project was to provide a rapid qualitative assessment of land management interventions on Ecosystem Services (ES) proposed for inclusion in Environmental Land Management (ELM) schemes. This involved a review of the current evidence base by ten expert teams drawn from the independent research community in a consistent series of ten Evidence Reviews. These reviews were undertaken rapidly at Defra's request and together captured more than 2000 individual sources of evidence. These reviews were then used to inform an Integrated Assessment (IA) to provide a more accessible summary of these evidence reviews with a focus on capturing the actions with the greatest potential magnitude of change for the intended ES and their potential co-benefits and trade-offs across the Ecosystem Services and Ecosystem Services Indicators.

The final IA table captured scores for 741 actions across 8 Themes, 33 ES and 53 ES-indicators. This produced a total possible matrix of 39,273 scores. It should be noted that this piece of work is just one element of the wider underpinning work Defra has commissioned to support the development of the ELM schemes. The project was carried out in two phases with the environmental and provisioning services commissioned in Phase 1 and cultural and regulatory services in a follow-on Phase 2.

Due to the urgency of the need for these evidence reviews, there was insufficient time for systematic reviews and therefore the reviews relied on the knowledge of the team of the peer reviewed and grey literature with some rapid additional checking of recent reports and papers. This limitation of the review process was clearly explained and understood by Defra. The review presented here is one of the ten evidence reviews which informed the IA.

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Contents

Index of Action Codes in this Report

1 INTRODUCTION

This review covers the air quality ecosystem services assessments where a full assessment of the impact of a particular intervention was needed. The three indicators assessed in the exercise are: reduced $PM_{2.5}$, reduced emissions of ammonia and air pollutants removed. Assessments were undertaken in the areas of soil management and protection, fertiliser, nutrients, manure and mulch management, specific wildlife targeted actions, restoration management and enhancement, drainage irrigation and wastewater, and systems actions. Actions to be reviewed were selected due to the direct effect on the AQ indicators, however it was noted that many other interventions will affect air quality either to improve indicators or deteriorate.

Ammonia is an important precursor of secondary inorganic aerosols and greatly impacts nitrogen deposition, Ammonia is a highly reactive and water-soluble alkaline gas. It originates from both natural and anthropogenic sources, with the main source being agriculture, e.g. livestock housing emissions, manure and fertiliser application. Excess nitrogen can cause eutrophication and acidification effects on semi-natural ecosystems, which in turn can lead to species composition changes and other deleterious effects (Bobbink et al., 2010; Krupa, 2003; Pitcairn et al., 1998). Ammonia can also be taken up through the leaves *via* stomata, increasing the potential for nutrient N uptake. The consequences of foliar uptake and processing of an alkaline gas for cellular functions drive the deleterious effects of exposure to ammonia above safe thresholds (above UNECE Critical Levels of Ammonia) on terrestrial plants. Air pollution from agriculture was reviewed recently by Defra's Air Quality Expert Group (Defra AQEG 2018).

For the purposes of this report, in general a reduction of emissions of ammonia will lead to a reduction in $PM_{2.5}$ due to the ammonia gas being a precursor chemical to the formation of particles (e.g. ammonium nitrate) which $PM_{2.5}$ comprises of. If an action specifically removes another air pollutant from the air then this will be noted, however not all or any specific other air pollutants are discussed as the topic would be rather wide. Reactions and interactions of the many different pollutant chemicals in the air are not reviewed as well as not all potential consequences of each measure on $PM_{2.5}$ precursor emissions has been flagged or discussed. For example, NOx, volatile organic chemicals and future chemistry are not explicitly mentioned so there are many caveats to the brief assessment presented here. This means that the only cases where the score for "Reduced emissions of ammonia" and "Reduced $PM_{2.5}$" differ is where there are effects on primary $PM_{2.5}$ emissions. Furthermore, for the purpose of this report 'Air pollutants removed' has been coded only with respect to active removal e.g. through canopy capture. It does not include avoided or reduced emissions. A further constraint applied here is that footprints of manufacturing or transport relevant to individual actions have not been considered, only the impact of the action as applied on the farm.

2 Outcomes

Primary outcomes the theme will review and assess (related to Ecosystem Services).

Service	Indicator for services flow
Air Pollution	Reduced $PM_{2.5}$
	Reduced emissions of ammonia
Air Quality	Air pollutants removed

3 Management Bundles

Options have been aggregated under the following management bundles:

- Drainage, irrigation and wastewater
- Fertiliser, nutrient and manure management
- Habitat creation
- Livestock management
- Restoration, management and enhancement
- Soil management and protection
- Systems action

3.1 Bundle: Drainage, irrigation and wastewater

This bundle encompasses wash and scrape fouled collecting yards after each use except where farms are subject to the provisions of the Industrial Emissions Directive (**ECAR-024**) and therefore reduced emissions. The impact is primarily the reduction of ammonia gas emissions, but also $PM_{2.5}$ by association as ammonia is a precursor to $PM_{2.5}$) to the environment and consequently less air pollution. In yards, the management of wastes can also reduce primary emissions of $PM_{2.5}$ dust.

3.1.1 ECAR-024 Wash and scrape fouled collecting yards after each use except where farms are subject to the provisions of the Industrial Emissions Directive

The impact of reducing ammonia emissions by scraping or washing a yard or animal lot has been well evidenced (Burchill et al., 2019; Galama et al., 2020; Ross et al., 2021; Varma et al., 2021). There are two main types of scraping: manual and automatic and various approaches to wastewater manure flushing. For some farming industries flushing is standard practice (e.g. milking industry in California) whereas in many regions manual or automatic scraping of waste from yards is implemented. Ross et al. (2021) and other studies evidence that manure flushing is more effective for reducing ammonia emissions reduction than scraping, and that manual scraping is more effective that automatic scraping. Interval between excreta deposition and farmyard cleaning is important for ammonia reduction (Burchill et al. 2019).

3.1.1.1 Causality

There is a causality for reduction of ammonia gas emissions in the literature which as reported, for example Burchill et al. (2019) demonstrated that power washing can reduce ammonia emission by ~80%- 90% if washed within 1 or 3 hours. Scraping reduced by 78% and 54% respectively. Ammonia emissions from liquid stored manure can occur rapidly due to hydrolysis of urea and slowly via organic nitrogen mineralisation. Emissions from slurry manure are higher than liquid stored manure due to the difference in total solids and higher mineralisation (Balde et al., 2018; Grant and Boehm, 2020). However, there are rather few studies across the range of practices and application across sectors therefore the evidence is limited for the action. (**ECAR-024** **AMBER**)

3.1.1.2 Co-Benefits and Trade-offs

The scraping and washing of a yard also impact the emissions of methane and carbon dioxide, and nitrous oxide to a lesser extent (and fewer studies were found in this topic). Scraping has higher emissions than flushing (e.g. Ross et al. (2021). Compared to flushing systems, scraping systems use significantly less or no water. Animal hygiene has been studied for different management techniques with flushing having better animal health outcomes.

3.1.1.3 Magnitude

Deposition of livestock urine and dung on concrete farmyards has been identified as a significant source of ammonia emissions which is estimated to account for almost 10% of agricultural ammonia emissions for Ireland and the UK (Misselbrook et al., 2006). Magnitude of the impact of reduction of ammonia emission from the process (either scrape or flush) can be large (up to 90% *c.f.* that which would be emitted without a flush or scrape process regularly undertaken. However, this is only for that specific process emission, which is the first part of the manure handling process – followed by storage, treatment and spreading.

3.1.1.4 Timescale

The prompt cleaning of the area whether yard or stall proportionately decreases the emissions, therefore once process implemented emission reduction from process would be immediately reduced (see references above).

3.1.1.5 Spatial Issues

The flushed and scraped waste requires storage to manage emissions, i.e. either on-farm storage or collection and repositing waste in management facilities farm requires storage for either the flushed or scraped waste on farm. Where farms rely on solid waste handling in covered yards – essentially animals are housed on solid bedding which is not removed until the end of the housing period - scraping is not practicable. Flushed waste removal requires additional storage facilities as the volume of waste is increased. There are risks of increased water pollution if handling and storage are not well managed.

3.1.1.6 Displacement

The removal of waste from yards to reduce emissions could be displaced if the waste management processes are not also managed post removal.

3.1.1.7 Maintenance and Longevity

All mechanical or manual scraping or flushing systems will require on-going maintenance to ensure safe and effective operations

3.1.1.8 Climate Adaptation or Mitigation

Due to the volatility of ammonia, the process would ideally be done more frequently in hotter weather to maintain the same level of emission reduction

3.1.1.9 Climate Factors / Constraints

See above.

3.1.1.10 Benefits and Trade-offs to Farmer/Land manager

Reducing ammonia emissions via scraping would reduce GREENHOUSE GAS emissions from the same source and if process managed well have potential to improve animal health in locations such as stalls and milking parlours. However, that is dependent on method applied.

3.1.1.11 Uptake

Farms are more likely to take up flushing or scraping systems where it improves good farm management rather than for the reductions of emissions purpose only (Lyon et al. 2016). Additional handling and storage requirements require investment.

3.1.1.12 Other Notes

None.

3.2 Bundle: Fertiliser, nutrient and manure management

This bundle encompasses calculating a whole farm nutrient balance for phosphorus and nitrogen, taking into account nutrient inputs from feed, fertiliser and manures and outputs in crop and livestock products. It also involves comparing nutrient use efficiency and nutrient balances with other similar farms and taking action to improve it. Improved nutrient balances can result in reduced fertiliser input and therefore reduced emissions (mainly of ammonia but also $PM_{2.5}$ by association as ammonia is a precursor to $PM_{2.5}$) to the environment and as a consequence less air pollution.

3.2.1 ECCM-004: ECPW-235: ECPW-274: ECPW-299: Soil management and protection / fertiliser, manure and mulch management

Four actions are discussed combined together as some are too high level or duplicates of each other.

ECCM-004: Nutrient Management Plan
ECPW-235: Calculate whole farm nutrient balance for phosphorus and nitrogen, taking account of nutrient inputs from feed, fertiliser and manures and outputs in crop, and livestock products
ECPW-274: Compare nutrient use efficiency and nutrient balances with other similar farms and take action to improve it
ECPW-299: Spatially test soils within field for any or all of the following chemical parameters: N, P, K, Mg, pH, micronutrients, potentially toxic elements and organic matter.

Each of these actions require management and measurement plans and **ECPW-235** and **ECPW-274** could be considered tasks within **ECCM-004**. **ECPW-299** is the evidence base on which the others are calculated and **ECCM-004** reviewed. Just having a plan does not necessarily result in improvements. A plan should be followed through with measurements and monitoring in order to assess its effectiveness.

3.2.1.1 Causality

Applying models to calculate whole farm nutrients budgets also requires some measurements for inputs, therefore each action would need to be very specific to achieve outcomes desired and the pressures for uptake are many fold and not necessarily related to air pollution. (e.g. Gao and Arbuckle, 2021). Regardless of the definition of the systems to which nutrient budgets and measurements are applied, they are usually difficult to balance, often leading to significant “missing” nutrients (Zhang et al. 2020). There are few studies evidencing reduction of ammonia emissions through use of NMPs and associated actions (Guo et al. 2020; Xu et al. 2022). Xia et al. (2017) undertook a meta-analysis of knowledge-based N management to reduce reactive nitrogen pollution and found that this can be considered an effective method (**ECPW-004** **GREEN**). However, it is noted that the majority of published studies are based in Asia.

The nature of nutrients and rates of their conversion vary between and within cycle components, and consequently imbalances occur, causing undesired nutrient losses to or extractions from soil, water and air (Tamminga, 2003). Calculating nutrient budgets on farms can have benefits as excess nutrients will be lost to the environment and cause pollution. Undertaking a nutrient management plan is recommended within the UK CoGAP (UK, 2018) and is being actively implemented in the US to minimise water and air losses. However, just having a plan is not sufficient, it needs to be followed through with actions, hence measurements and monitoring are needed as part of the action in order to be able to assess effectiveness. Based on crop nutrient requirements and soil nutrient supply, the amounts of manure N and P that could be applied to available land can be calculated (Jia et al. 2017). Over-application should be avoided as that would result in likely losses to the environment, especially as ammonia and by association as $PM_{2.5}$. Using a nutrient budget model for farms can calculate ammonia loss (Sonneveld et al. 2008). Knowing the nutrient budget of a farm can suggest interventions to improve nutrient use and minimise losses, i.e. pollution, if the plan is followed by actions (Yorgey and Kruger 2020). Comparing nutrient budgets from one farm with another is very difficult as so much depends on the conditions on each farm as well as environmental conditions, hence it is not assessed here. As for spatially testing soils, this will be context dependent and requires targeting to be effective. There are limited references available and generalisation is therefore not possible. None of these actions would result in active removal of air pollutants. However, it should be noted that if due to a known farm nutrient budget chemical fertiliser input can be reduced, it will likely also reduce emissions of other air pollutants, such as VOCs (Fieberg et al. 2015). (**ECPW-235** **Amber;** **ECPW-274** **AMBER;** **ECPW-299** **AMBER**)

3.2.1.2 Co-Benefits and Trade-offs

Improving nutrient use efficiency will likely also improve/reduce greenhouse gas emissions, especially nitrous oxide (Tamminga, 2003). Water pollution risks can also be reduced. Improving nutrient use efficiency has the potential for reducing the level of manufacture and transport of fertiliser which will have a positive impact on air pollution.

[TOCB Report-3-5B *Grassland* **ECPW-299**] Assuming this leads to precision application of crop nutrients, positive benefits for biodiversity.

[TOCB Report-3-5D *Systems* **ECPW-235**] This is a general plan for management that will lead to positive or neutral effects on biodiversity if conducted appropriately.

3.2.1.3 Magnitude

Magnitude of the impact will vary depending on how much information is available to constrain a whole farm budget and if interventions are needed to improve the nutrient budgets. Most importantly it depends on potential actions following a plan or test results from spatial soil samples. The level of implementation of each of the actions would also affect the magnitude of the effect of the action and there is much uncertainty in nutrient management plan implementation and is the subject of many social science studies e.g. Daxini et al. (2019). Xia et al. (2107) evidenced 9-53% reduction in ammonia emissions.

3.2.1.4 Timescale

See above, it depends on how well a nutrient management budget can be constrained and what interventions might have to be taken. This bundle is a tool rather than a solution but implemented with plan revisions, air pollution could be reduced within a few years.

3.2.1.5 Spatial Issues

Only possible per farm and likely difficult to extrapolate unless farm management, location, etc. very similar or a programme of application to nitrogen management applied over regional and commercial networks of farms.

3.2.1.6 Displacement

Improving nutrient use efficiency on one farm should not result in displacement.

3.2.1.7 Maintenance and Longevity

To calculate a nutrient budget for a farm, input parameters should be updated annually or whenever anything changes but it can be used long term to highlight interventions needed.

3.2.1.8 Climate Adaptation or Mitigation

Input parameters needed for the calculation could change due to climate adaptation or mitigation measured.

3.2.1.9 Climate Factors / Constraints

See above, might have an impact on input needed for calculations.

3.2.1.10 Benefits and Trade-offs to Farmer/L-and manager

Calculating a whole farm nutrient budget can benefit the farmer in that less chemical fertiliser might need to be purchased if it is known, for example, how much nitrogen and phosphorous is present in manure, resulting in a cost-saving for the farmer (Jia et al., 2017).

3.2.1.11 Uptake

It is likely that the farmers will need somebody to do the calculations for them (unless easy tools such as mobile Apps available) or need measurements to determine phosphorous and nitrogen concentrations in different inputs and outputs which will likely result in a monetary cost. Potential savings in costs for chemical fertilisers need to be weighed with the costs to establish a nutrient budget in order to promote uptake.

3.2.1.12 Other Notes

Requires a lot of knowledge about nutrient contents in farm inputs and outputs which might be a barrier. Timing of the application of manures and fertilisers in relation to crop status and soil temperature is also important to ensure efficient uptake by crops.

3.3 Bundle: Habitat creation

Habitat Creation – Agroforestry:	**ECAR-032:** Create agroforestry systems
Habitat Creation – Woody Features:	**EBHE-205C:** Create wood pasture
	ECPW-156C: Plant trees and shrubs around point-source polluters
	ECAR-033C: Create Shelter belts near sensitive habitats
	ECAR-047: Create/enhance/manage shelter belts on hill slopes
Habitat Creation – Hedgerow:	**ECCM-080C:** Plant hedgerows around point-source polluters

This bundle covers the impact of agricultural shrubs and trees on air pollution removal. This includes the targeted use of the vegetation to capture some emissions at source (**ECPW-156C**), on hillslopes (**ECAR-047**) and near sensitive habitats (**ECAR-156C**), as well as the impact of agroforestry on air pollution, both generally (**ECAR-032**) and for wood pastures in particular (**EBHE-205C**). In general, increases in vegetation cover increases the removal of most air pollutants compared with un-vegetated surfaces and removal tends to be more efficient for tall vegetation such as trees than for short vegetation such as grass. Thus, habitat creation focussed on the creation of new trees, scrubs, hedges and woodlands in a range of contexts (around sources, to shelter sensitive habitats and in the context of agroforestry) has the potential to impact positively on air quality by removing pollutants during transport from point of emission to the point where it impacts on ecosystems and/or human health. Such woodland features often also generate additional turbulence that increases dispersion which reduces surface concentrations and thus exposure to air pollution, but it can also result in wind sheltering and local accumulation of pollutants. Removal by vegetation is generally more effective at source where concentrations are large and where optimised designs can maximise the contact between pollutants and vegetation, than at receptor sites where concentrations are smaller.

Much of the evidence of the impact of vegetation on air pollution concentrations comes from the study of the urban environment, where there is much interest in the potential of nature-based solutions and green infrastructure for air pollution remediation. Nationally, vegetation has a significant impact on air quality (Jones et al., 2017), however, to affect regional concentrations of pollutants, vegetation needs to be introduced or changed at very large scales limiting the impact at least in the urban context (Nemitz et al., 2020;AQEG, 2018). Individual, small-scale intervention tend to have very limited impacts on local air quality (Vos et al., 2013) localised being a very local reduction, (<100 m) rather than locality (landscape).

As a downside, many tree species are emitters of biogenic volatile organic compounds which are precursors of $PM_{2.5}$ (with human health impacts) and tropospheric ozone (with impacts on human health, ecosystems and crop yields). There is scope, through the selection of particular plant/tree species and woodland feature designs to maximise the potential for air pollutant capture whilst minimising the biogenic volatile organic compounds emissions (Kumar et al., 2019).

In addition, capture of nitrogen compounds, in particular of agricultural ammonia, by such woodland features can result in the accumulation of nitrogen in these new habitats which can lead to pollutant swapping by increasing the emission of soil nitrogen oxides (again involved in the formation of $PM_{2.5}$ and ozone) as well as nitrous oxide, a potent greenhouse gas, and it can also increase nitrogen leaching to surface and ground water. Hedges, shrubs and woodland features specifically designed for the capture of ammonia will be subject to exceedances in the critical loads and levels for nitrophobic plant communities resulting in reduced biodiversity within these agricultural shrub / wood features.

3.3.1 ECAR-032: Create agroforestry systems

Agroforestry is a catchall for land management approaches that combines trees and shrubs with crop and livestock farming systems. It covers a wide range of systems and designs and, under UK conditions, includes in particular hedges, silvoarable cropping, contour planting, woodland eggs/chickens and other silvopastural designs. Wood pasture are dealt with separately under **EBHE-205C**. In the UK, in particular woodland eggs, woodland chickens and, more recently, woodland pork have gained market share (Burgess, 2017).

3.3.1.1 Causality

Depending on the type of agroforestry system, due to the wide range of agroforestry systems, evidence of their impact on air quality exists for some settings, but not on others (**ECAR-032** **AMBER**). Agroforestry has the potential to lower emissions of key air pollutants. In particular, ammonia emissions are reduced where temperature is reduced through shading (Sutton et al., 2013), and where turbulence is reduced through sheltering (Theobald et al., 2004b;Bealey et al., 2014). It can also recapture some primary PM emissions from tilling activities as well as pesticides and herbicides (Ellis and Van Dijk, 2009). However, the effectiveness of agroforestry for capturing air pollutants depends hugely on the exact layout, which needs to be carefully designed for the purpose of air pollution recapture to maximise its potential. If poorly designed for this purpose, the emissions abatement will often be negligibly small.

Only few individual agroforestry designs have been studied, mainly with respect to their potential to reduce / recapture agricultural ammonia emissions. In particular, the effect of keeping animals under tree canopies has been demonstrated in a very limited number of measurement and modelling studies (Bealey et al., 2015;Bealey et al., 2014;Bealey et al., 2016). Whilst the scientific processes involved are fairly well understood, direct verification of the effect through measurements is difficult and data are sparse. There are no generally accepted measurement approaches to demonstrate efficacy, and a need to derive low-cost approaches for monitoring against robust, detailed scientific approaches. For keeping animals under closed canopies, the state of knowledge is AMBER.

It is noted due to the myriad of agroforestry systems available, many agroforestry systems have not been studied at all therefore the principle would need to be applied using both atmospheric physics and biology to plan agroforestry interventions to reduce ammonia and PM emissions.

3.3.1.2 Co-Benefits and Trade-offs

In addition, the capture of ammonia could lead to large nutrient inputs with adverse consequences for nitric oxide emission (trade-off for Air Quality itself), nitrous oxide (trade-off for climate) and nitrogen runoff to ground and surface water. In general, forest soils tend to be subject to larger emissions of nitrogen oxide than other soils. A review of the literature suggests that tree roots in agroforestry systems are able to reduce nitrogen and phosphorus residues in soils from 20 to 100% and have the potential to reduce pesticide leaching and runoff considerably (Pavlidis and Tsihrintzis, 2018). That study, however, did not take into account any potential increases in emission to air. Also, direct measurement evidence is variable. For example, some indication was found of increased N leaching from chickens kept under short rotation coppice willows compared with open pasture (Stadig et al., 2019).

Agroforestry shrubs and trees would likely be subject to inputs of agricultural nitrogen (mainly via ammonia) in excess of N critical loads and levels. Although agricultural woodland would likely have a positive impact on biodiversity (e.g. nesting sites for birds), their species composition will be impacted by the N and thus large-scale increase in agricultural woodland could result in a larger absolute and relative proportion of the UK's woodland to be subject to exceedances of critical loads / levels, thus leading to perverse consequences for current metrics. For this reason, the concept of 'sacrificial woodlands' has been floated which may be treated separately in the ecosystem assessments. Overall, the impact of ammonia on biodiversity is well understood (e.g. Guthrie et al., 2018). At very high N deposition the health of the shrubs / trees itself may suffer (Krupa, 2003).

3.3.1.3 Magnitude

Few agroforestry options have been assessed in terms of their potential to reduce agricultural air pollution emissions. Bealey et al. (2016) estimated that 45% ammonia capture efficiency of the grazing emissions could be achieved for under-canopy silvo-pastoral farming systems. If small poultry arcs were placed under the tree canopy, a similar reduction would apply to the poultry housing emissions. This was estimated, based on measurements and detailed modelling using a fairly idealised / optimised design (Bealey et al., 2014), for a 10 m tall tree canopy formed from a 100 m grazing canopy with a leaf area index (LAI) of 3 with a 50 m deep backstop canopy with an LAI of 6. For sparser or leafless canopies and designs without a backstop (to effectively filter the air that may horizontally escape from the trunk space) the efficiency might be much smaller.

In many agricultural systems not specifically optimised for the capture of emissions the benefit for air pollution can be negligible. There is a body of literature on the pollution removal by hedges based on measurement and modelling. Much of this is focussed on particulate matter and the urban environment (e.g., Tiwary et al., 2006;Guo and Maghirang, 2012). Results indicate that the only effect of hedges is that they may retain a few % of $PM_{2.5}$ and a bit more of coarse PM only of the air mass that actually travels through the hedge. For hedges around fields this is a negligible effect, but it could become more significant, also for ammonia retention, for silvoarable cropping, with regular hedges / tree belts. The effectiveness would likely significantly vary with the direction of these hedges (ideally perpendicular to the prevailing wind direction) hedge thickness and plant species.

3.3.1.4 Timescale

Development to maturity of the agroforestry system, which is frequently 10 years or more. Trees need time to mature to achieve the sort of LAI and fairly closed canopies that is required for effective ammonia abatement for animals under tree cover. Similarly, constraints would apply to silvoarable cropping designs and hedges.

3.3.1.5 Spatial Issues

The efficiency of agroforestry is highly dependent on the exact spatial layout and proximity to sources.

3.3.1.6 Displacement

The local capture of agricultural ammonia will shift the environmental impacts on biodiversity, tree health, pollution swapping (conversion to nitric oxide and nitrous oxide) and aqueous phase nitrogen run-off, from further afield to the on-farm vegetation. This may be desirable, however, to protect more sensitive ecosystems elsewhere and reduce the potential of ammonia as a precursor to $PM_{2.5}$.

3.3.1.7 Maintenance and Longevity

Maintenance of the shrub/tree elements forms an integral part of agroforestry. To maximise the potential for pollution capture, this maintenance would need to specifically take pollutant capture into account. Guidance of how to optimise maintenance is lacking.
Agroforestry systems can often be maintained over long times. Trees and hedges will take time to develop a canopy that is sufficiently dense to capture air pollutants. However, as trees mature their structure may diverge again from the optimum design and some replanting may be required.

3.3.1.8 Climate Adaptation or Mitigation

Evidence on the effect of climate on pollutant recapture is lacking. Overall, ammonia emissions will increase with temperature (Sutton et al., 2013). Agroforestry will presumably need to adapt to climate change, e.g. in terms of species selection.

3.3.1.9 Climate Factors / Constraints

Ammonia recapture by vegetation is particularly effective when plant canopies are wet. Some of the tradeoffs (aqueous nitrogen run-off and nitric oxide/nitrous oxide emissions) are highly dependent on meteorology. However, since these have not yet been quantified, the impact of climate on these trade-offs is also not well understood.

3.3.1.10 Benefits and Trade-offs to Farmer/Land-manager

The benefit of air pollution mitigation by agroforestry has to be assessed within the fuller economic analysis of agroforestry and its products. This depends on market forces and opportunities (e.g. marketing of woodland eggs). Overall, keeping nitrogen within the on-farm system could lower the need for fertiliser. It is possible that the optimisation for pollution capture would require some input that would not translate into economic return.
There is some evidence that providing hedge access to free ranging broilers results in increased growth without an associated increase in intake or cost of feed thus at least partly offsetting the larger cost of this management (Delgadillo et al., 2021).

Government grants are already available for planting trees in the entire ranging area of free-range poultry or pigs as Countryside Stewardship Mid-Tier and Capital Grants, with Catchment Sensitive Farming (CSF) approval.

3.3.1.11 Uptake

No assessment.

3.3.1.12 Other Notes

The impact of agroforestry on emission mitigation is highly dependent on the exact implementation of the agroforestry system. Thus, if agroforestry was to be adapted as an option for farmers to reduce their ammonia emissions from the farming system there would need to be a cost-effective monitoring approach to demonstrating its efficacy.

3.3.2 EBHE-205C: Create wood pasture (e.g. through appropriate grazing)

Wood pasture is a specific system under the wider umbrella of "agroforestry" which is covered under **ECAR-032**. There the general benefits and trade-offs of agroforestry systems are discussed, with some emphasis on keeping animals under tree canopies, a system which is both gaining in popularity and for which some evidence exists. That sort of management system could also be considered a wood pasture, but, traditionally, wood pastures are more open, established habitats with mature trees and/or scrub as individual plants or clumps, dotted around pastures to provide shelter and fodder for livestock similar to typical parkland and it is this priority habitat, as defined in the UK Biodiversity Action Plan (BRIG, 2011), that is considered here in the context of "woody features".

3.3.2.1 Causality

The impact of wood pastures on air quality, and in particular the recapture of agricultural ammonia emissions, is similar to that of keeping animals under closed canopies discussed under **ECAR-032**, except that mature wood pasture canopies are much more open and sparse and therefore likely to be much less efficient in reducing and recapturing grazing ammonia emissions. There will be localised effects on sheltering and shading, thus reducing emissions in the first place, and some localised re-capture, but extrapolation of the reasoning behind the idealised designs for recapture (Bealey et al., 2016;Bealey et al., 2015;Bealey et al., 2014) would suggest that woodland pastures are fairly inefficient in recapturing grazing emissions. There is limited evidence, benefits will be context dependant and if implemented poorly, disbenefits may be observed. (**EBHE-205C** **AMBER**).

Wood pastures, as partly wooded landscapes, will have a general, but small, role in taking up air pollutants. Their efficiency in taking up air pollution is likely akin to urban parks, which have a similar mix of trees and grass surfaces, but their total uptake of most pollutants would depend on the concentration: it would be likely be larger for agricultural pollutants and lower for urban air pollutants. There is a range of opinion on the pollutant removal by urban parks (Xing and Brimblecombe, 2019;Pallozzi et al., 2020;Fares et al., 2020) and uncertainties around the parameterisations used for the assessment. Their scale and heterogeneity makes the reliable quantification of pollutant uptakes in woodland pastures (and parks) very difficult.

This action might also involve turning existing continuous forests into wood pasture (through appropriate grazing). In this case, existing understory vegetation and some of the existing trees may be removed and the efficiency of the wood pasture in taking up (non-grazing) air pollutants may be reduced compared with the original forest. Either way, although uncertainties are large, the overall impact is very likely not large.

3.3.2.2 Co-Benefits and Trade-offs

Same as for agroforestry systems in general discussed under **ECAR-032**, but at a reduced scale because ammonia recapture is smaller than what would be achievable with more targeted agroforestry designs.

3.3.2.3 Magnitude

Likely very small as not optimally designed for air pollution capture.

3.3.2.4 Timescale

Woodland pastures are typically characterised by mature trees. This action is likely either about maintaining and retaining existing wood pastures or turning existing forest into wood pastures. The former would have no timescale associated with it, the latter could be achieved within the 0-5 year timescale.
For establishment of new wood pastures, the time scale would be >10 years: trees need time to mature to achieve the sort of LAI for effective pollutant uptake.

3.3.2.5 Spatial Issues

This action is unlikely to have a large impact on reducing emissions or air pollution and air quality and these benefits should be considered within the context of other benefits. There is likely a limited number of habitats / areas that lend themselves to conversion to wood pastures.

3.3.2.6 Displacement

As in the case of agroforestry, the local capture of agricultural ammonia will shift the environmental impacts on biodiversity, tree health, pollution swapping (conversion to nitric oxide and nitrous oxide) and aqueous phase nitrogen run-off, from further afield to the on-farm vegetation. This may be desirable, however, to protect more sensitive ecosystems elsewhere and reduce the potential of ammonia as a precursor to $PM_{2.5}$.

3.3.2.7 Maintenance and Longevity

There would be on-going long-term maintenance required, however well-managed a woody pasture system is a long term and sustainable approach.

3.3.2.8 Climate Adaptation or Mitigation

No assessment.

3.3.2.9 Climate Factors / Constraints

Ammonia recapture by vegetation is particularly effective when plant canopies are wet. Some of the tradeoffs (nitric oxide and nitrous oxide emissions to air and aqueous phase nitrogen run-off) are highly dependent on meteorology. However, since these have not yet been quantified, the impact of climate on these trade-offs is also not well understood.

3.3.2.10 Benefits and Trade-offs to Farmer/Land manager

No assessment.

3.3.2.11 Uptake

No assessment.

3.3.2.12 Other Notes

None.

3.3.3 ECPW-156C: Plant trees and shrubs around point-source polluters

Trees and shrubs take up air pollutants at a rate that is higher than shorter vegetation, such as grass. Where these trees and shrubs are planted for this purpose, several terms have been used to describe this ranging from sacrificial woodland, vegetative environmental barriers (VEBs, e.g. Ro et al, 2018; Coletti et al. 2006) and tree belts. The uptake scales with concentration and thus their potential to remove air pollutants is largest at source where concentrations are largest. Trees and shrubs can also provide shading which reduces emission processes that are controlled by temperature, such as ammonia emissions from livestock wastes and fertilisers. Similarly, trees and shrubs can provide shelter to reduce turbulence that would stimulate ammonia emissions from open lagoons (Bealey et al. 2014; Tyndall and Coletti, 2007).

3.3.3.1 Causality

The evidence for the capture of ammonia and PM with trees and shrubs near agricultural point sources is limited. Removal of other pollutants and other pollution sources has less evidence (**ECPW-156C: AMBER**).

There have been some studies into the capture of ammonia by on-farm woodland and shelterbelts and the underlying processes are reasonably well understood. The measurement and modelling work so far has highlighted the need to carefully chose tree species and optimise the layout to maximise the contact of the released ammonia with the plant canopy (Theobald et al., 2004b;Bealey et al., 2015;Bealey et al., 2016;Bealey et al., 2014).

Some thinking has gone into optimised designs[1] but large-scale field validation is still lacking. There are no generally accepted measurement approaches to demonstrate efficacy, and a need to derive low-cost approaches for monitoring against robust, detailed scientific approaches.

Similarly, the impact of wind breaks on reducing ammonia volatilisation has been modelled in relation to the height of the wind break, the turbulence reduction and the size of the lagoon (Theobald et al., 2004a). Covering lagoons provides a more complete solution to reducing ammonia emissions (Kupper et al., 2020).

Less evidence exists for the efficacy of trees and shrubs to reduce the emission or recapture emissions of other pollutants including $PM_{2.5}$ or the efficacy for emissions from non-agricultural point sources. However, in theory odour and PM could interact with the surfaces of trees and shrubs (Yao et al. 2014). Whilst tree planting around agricultural point sources would also reduce primary PM emissions there have been limited studies. Willis et al. (2017) reported that periodic lofting above the buffer was shown in lidar scans and the vegetative environmental buffer (VEB) was more effective at night, when low turbulence and wind speed were observed. VEB capture efficiency in Willis et al. (2017) for PM varied between 21% and 74% for a broiler house and a surrogate dust release (kaolinite) with a VEB downwind. These results were in a similar range to a wind tunnel study (Malone et al., 2006) and at a swine facility (Hernandez et al., 2012).

There is more evidence for PM interactions from studies focussing on the recapture by hedges and trees in the urban context, e.g. along roads, which constitute line rather than point sources (AQEG, 2018). In principle, however, the insights into ammonia recapture from point sources can be translated to other contexts making allowance for emission height and the uptake rate of the various emitted pollutants.

3.3.3.2 Co-Benefits and Trade-offs

The same co-benefits and trade-offs apply as for the use of trees / shrubs in the agroforestry setting (**ECAR-032**).

3.3.3.3 Magnitude

For ammonia point sources, a screening tool to estimate the percentage ammonia recapture that may be expected by a downwind shelterbelt with or without backstop (denser downwind canopy) is available[2], as a function of shelter belt dimensions, tree species, soil type and location. Field validation is limited and the uncertainty range provided with the prediction is large. According to this tool, recapture of 25% (+/-13%) is feasible with ideal designs and fully developed, healthy canopies. Poor designs, however, can result in negligible benefits and demonstration of the benefit through a sound (but yet undeveloped) monitoring method would be important.

Using an atmospheric chemistry and transport model with modified landcover and assuming an ammonia recapture of 20%, Bealey et al. (2016) showed that large scale on-farm emission reduction through tree planting could result in a reduction of UK national nitrogen deposition to semi-natural areas of 0.14% to 2.2%. Here mitigation was highest for cattle and pig housing.

[1] e.g. www.farmtreestoair.ceh.ac.uk/sites/default/guidance/index.html
[2] www.farmtreestoair.ceh.ac.uk/ammonia-reduction-calculator

Vegetation removes different pollutants with different efficiencies and is lower for most pollutants than it is for ammonia which is fairly water soluble and can be taken up through stomata. Efficiencies are lower for fine particles ($PM_{2.5}$) and nitrogen dioxide, very low for nitric oxide, but potentially higher for coarse particles (PM_{10} and total suspended particulate, TSP) and highly water-soluble gases such as nitric acid and hydrochloric acid.

Most importantly, the capture efficiency depends on the air pollutant release height relative to the tree / shrub vegetation heights. Capture efficiency is more efficient for ground-level emissions than for stack emissions and geometries where the plume passes through the largest volume of vegetation. If a chimney or vent height is above the height of the surrounding canopy, an air pollution capture will not happen. It is worth noting that chimneys and rooftop vents are designed to maximise effective height and buoyancy and that disturbing this with vegetation could be counterproductive with respect to local (but not regional) effects.

3.3.3.4 Timescale

The timescale of effectiveness of trees and shrubs is the time for development of the vegetation canopy for maximum recapture (as discussed above). Generally, this would be ~10 years minimum. Maximum emission capture of the order of 20% ammonia would only be achievable with well-developed dense canopies. However, adaptation of plantings of trees for other purposes (see agroforestry) can lead to faster results.

3.3.3.5 Spatial Issues

An optimised spatial design is crucial for the efficacy of recapture of emissions by trees and shrubs. The planting of woodland around agricultural point sources appears to be a measure that can be implemented at fairly large scales across the country but will result in some loss of productive agricultural land. For large scale implementation the accounting of the compromised health / ecological state of these woodland features needs to be dealt with. Establishment of shelter belts is likely less of a viable option for many non-agricultural point sources, which are often emitted at higher height and where land for planting is not as widely available as in the agricultural context.

3.3.3.6 Displacement

As in the case of agroforestry, the local capture of agricultural ammonia will shift the environmental impacts on biodiversity, tree health, pollution swapping (conversion to nitric oxide and nitrous oxide) and aqueous nitrogen run-off, from further afield to the on-farm vegetation. This may be desirable, however, to protect more sensitive ecosystems elsewhere and reduce the potential of ammonia as a precursor to $PM_{2.5}$.
The establishment of additional farm woodland will take agricultural land out of production.

3.3.3.7 Maintenance and Longevity

Emission capture of the order of 20% NH_3 would only be achievable with well-developed dense canopies. Aging canopies with open trunk spaces would likely again become less effective in capturing emissions, requiring regular maintenance (every few years) and replanting over time to maintain an optimum structure.

3.3.3.8 Climate Adaptation or Mitigation

As with silvoculture in general, the tree / shrub species suitable for planting across the UK will change as the climate changes and pathogens emerge. Species selection will need to adapt.

3.3.3.9 Climate Factors / Constraints

Ammonia recapture by vegetation is particularly effective when plant canopies are wet. Some of the tradeoffs (nitric oxide and nitrous oxide emissions to air and aqueous phase nitrogen run-off) are highly dependent on meteorology. However, since these have not yet been quantified, the impact of climate on these trade-offs is also not well understood.

3.3.3.10 Benefits and Trade-offs to Farmer/L-and manager

Taking land out of agricultural production would decrease losses. The shelter belts have some potential to create timber but would need to be managed to maximise their potential for pollutant capture rather than timber production. Government grants are already available for planting shelter belts for ammonia capture from slurry digestate stores or livestock housing as Countryside Stewardship Mid-Tier and Capital Grants, with Catchment Sensitive Farming (CSF) approval.

3.3.3.11 Uptake

No assessment.

3.3.3.12 Other Notes

The impact of shelterbelts on emission mitigation is highly dependent on the exact design and management. Thus, it would be important to produce improved guidance (based on more field and modelling evidence) and a cost-effective monitoring approach to demonstrate the efficacy in each setting.

3.3.4 ECAR-033C & ECAR-047: Shelter belts

ECAR-033C: Create shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition near sensitive habitats

ECAR-047: Create/ enhance/ manage shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition on hill slopes

With respect to air pollution and its effects, these actions relate mainly to the impact of agricultural ammonia on nitrogen sensitive habitats and a well-designed shelter belt designed to disperse and reduce ammonia concentrations can be effective as mentioned above, in terms of e.g. mass removed per tree, vegetation is more effective in reducing air pollutants at source (where concentrations are large) than near sensitive receptor sites. However, semi-natural vegetation usually acts as a sink for pollutants such as ammonia, where the agricultural landscape with point sources (farms, housing), grazed and/or fertilised fields acts as a source. Here shelter belts of semi-natural vegetation between agricultural areas and sensitive ecosystems have the potential to lower ground level ammonia concentrations as well as deposition loads.

In terms of its impact on air quality, we consider the creation of shelter belts on hill slopes as a special case of shelter belts near sensitive habitats.

3.3.4.1 Causality

Implementation of shelterbelt buffer zones around sensitive habitats reduces ammonia concentrations and loads for those habitats through three ways: by increasing the distance between the source and receptor region and thus allowing for dilution, by increasing turbulence and vertical dispersion, and by active uptake across the shelterbelt **(ECAR-033C GREEN; ECAR-047 GREEN).** The interaction of ammonia with semi-natural vegetation is fairly well understood (Flechard et al., 2013), but there are significant differences in the parameterisation between models which highlights uncertainty in the magnitude (e.g. Flechard et al., 2011). However, there is no doubt that as agricultural air moves over semi-natural vegetation, this vegetation acts as a net sink for ammonia. The sink is larger for rougher vegetation (shrubs and trees) than for smoother vegetation (semi-natural grassland).

The effect can and has been simulated through measurement and modelling studies in example landscapes (e.g. Sutton et al., 2004;Dragosits et al., 2002;Dragosits et al., 2005;Dragosits et al., 2006) through very high spatial resolution modelling of transport and deposition at a scale of 10s of metres. The potential has also been explored within Defra project AC109 (Future patterns of ammonia emissions across the UK and the potential impact of local emission reduction measures) (Dragosits, 2012) and is taken forward under the JNCC Nitrogen Futures Project[3].

3.3.4.2 Co-Benefits and Trade-offs

These are similar to the agroforestry systems (**ECAR-032**)

3.3.4.3 Magnitude

Model estimates of the potential reduction in ammonia concentration and deposition for sensitive habitats exist for the UK (Sutton et al., 2004;Dragosits, 2012) and also the Netherlands (Kros et al., 2015).
The largest impact is seen at the edge of the sensitive habitats because for further in the centre the sensitive habitats themselves act as a buffer for the inner-lying areas. As a result, the relative impact is larger on smaller sensitive habitats / SSSIs than on larger ones. Evidence suggests that buffer shelterbelts can reduce exceedance from critical loads of nitrogen and exceedance of the ammonia critical level of 3 µg m^{-3}, but are, at current ammonia background concentrations, insufficient to greatly improve protection at the 1 µg m^{-3} critical level for lichens and mosses.

3.3.4.4 Timescale

0-5 years with increase in effectiveness >10 years for shrubland / forest. Assuming that the shelterbelts are generated from previously cultivated land, it takes a few years for the nitrogen status to decline which is required for the shelterbelt to become an efficient sink for nitrogen compounds. >10 years would be required for shrubs and trees to grow to a height that their affinity for ammonia exceeds that of other semi-natural vegetation.

3.3.4.5 Spatial Issues

Shelter belts (or VEBs) tend to be of relatively small spatial scale, however modelling by Bealey et al (2014) showed that ideally a depth of 20-100 m downwind of the sources are the type of shelter belt which would be most effective. They would need to extend at least the length of the emission source.

3.3.4.6 Displacement

As in the case of agroforestry, the local capture of agricultural ammonia will shift the environmental impacts on biodiversity, tree health, pollution swapping (conversion to nitric oxide and nitrous oxide) and N run-off, from further afield to the on-farm vegetation. This may be desirable, however, to protect more sensitive ecosystems elsewhere and reduce the potential of ammonia as a precursor to $PM_{2.5}$.

3.3.4.7 Maintenance and Longevity

As with previous tree and shrub section, on-going management is required for the health and efficacy of the intervention.

3.3.4.8 Climate Adaptation or Mitigation

Climate resilient species would be a priority for planting for sustainability of the action.

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[3] www.jncc.gov.uk/our-work/nitrogen-futures/

3.3.4.9 Climate Factors / Constraints

Ammonia recapture by vegetation is particularly effective when plant canopies are wet. Some of the trade-offs (nitric oxide and nitrous oxide emissions to air and aqueous phase nitrogen run-off) are highly dependent on meteorology. However, since these have not yet been quantified, the impact of climate on these trade-offs is also not well understood.

3.3.4.10 Benefits and Trade-offs to Farmer/L-and manager

Benefits to farmers can be biodiversity, screening, or other income generation depending on the species and types of plantations.

3.3.4.11 Uptake

No assessment.

3.3.4.12 Other Notes

None

3.3.5 ECCM-080C: Plant hedgerows around point-source polluters

This is a specific case of the more generally worded action **ECPW-156C**: Plant trees and shrubs around point sources, with hedgerows being a specific arrangement of shrubs/trees. All the considerations discussed in previous sections above apply. In general, due to their restricted height, typical hedgerows of height 1-3 m are less efficient in recapturing emissions than shelter belt designs that incorporate taller tree elements. This is especially true for elevated sources (above ground level).

3.3.5.1 Causality

For surface emissions at ground level, it is possible that hedgerows can reduce ammonia emissions. For example, Lavrsen Kure et al. (2018) reduced nitrogen emission from applied nitrogen fertiliser from 2% to 1% on a plot scale study. Bell et al. (2016) noted hedge effects in an anaerobic digester ammonia emission study but this was not the primary focus of the study. Overall, there is limited evidence but in theory if designed appropriately, moderate reductions could be achieved from some ground level point sources (**ECCM-080C**: **AMBER**)

3.3.5.2 Co-Benefits and Trade-offs

No assessment

3.3.5.3 Magnitude

The magnitude of the reduction of either ammonia or a $PM_{2.5}$ plume would be small, but potentially locally important.

3.3.5.4 Timescale

Not assessed

3.3.5.5 Spatial Issues

Localised effects and design to minimise emissions from all directions would be needed.

3.3.5.6 Displacement

As in the case of agroforestry, the local capture of agricultural ammonia will shift the environmental impacts on biodiversity, tree health, pollution swapping (Some of the trade-offs including nitric oxide and nitrous oxide emissions to air and aqueous phase nitrogen run-off) from further afield to the on-farm vegetation. This may be desirable, however, to protect more sensitive ecosystems elsewhere and reduce the potential of ammonia as a precursor to $PM_{2.5}$.

3.3.5.7 Maintenance and Longevity

Hedgerows require on-going maintenance, however, are long term features in the landscape.

3.3.5.8 Climate Adaptation or Mitigation

3.3.5.9 Climate Factors / Constraints

There is some evidence of hedgerows sequestering carbon – a climate mitigation measure.

3.3.5.10 Benefits and Trade-offs to Farmer/Land-manager

Species composition and design of hedgerows can provide biodiversity, screening and foraging benefits. However, there is a cost to maintenance.

3.3.5.11 Uptake

No assessment.

3.3.5.12 Other Notes

None

3.4 Bundle: Livestock management

Livestock Management – Feeding strategies:

ECPW-145: Optimise livestock feeding strategy to match animal requirements, (e.g. protein, lipids) except where farms are subject to the provisions of the Industrial Emissions Directive
ECCM-069: Use more high starch and reduced crude protein in diets
ECCM-010: Use phase feeding of livestock
AQ-01: Free range poultry/pigs in woodland
ECAR-020: Extending cattle grazing season

Livestock Management – Housing & handling:

ECCM-008: Use improved livestock housing management practices (e.g. regular slurry scraping, washing down floors and yards, using electric or robotic scrapers) and store scrapings appropriately where business is not regulated under IED
ECAR-026: Use improved livestock flooring systems (e.g. slatted flooring and grooved floors or stand-off pads / woodchip for over wintering cattle as an alternative to slurry-based housing)
ECAR-027: Use improved livestock housing+ infrastructure to reduce emissions (e.g. ammonia scrubbers and biotrickling filters to mechanically ventilate housing) unless regulated under IED.
ETPW-224: Relocate livestock housing away from sensitive receptor sites
AQ-02: Monitor air quality pollution and greenhouse gas footprint of agricultural buildings to actively manage emissions
AQ-03: Monitor indoor concentrations of ammonia and greenhouse gas

3.4.1 ECPW-145: ECCM-069: ECCM-010

ECPW-145: Optimise livestock feeding strategy to match animal requirements, (e.g. protein, lipids) except where farms are subject to the provisions of the Industrial Emissions Directive
ECCM-069: Use more high starch and reduced crude protein in diets
ECCM-010: Use phase feeding of livestock

Feeding strategies directly link into air pollution emissions and in particular ammonia emissions. Groenestein et al. (2019) led a comparison of ammonia emissions related to nitrogen use efficiency of livestock production in Europe, which describes ammonia-nitrogen loss and nitrogen use efficiency (NUE) related to animal protein production instead of to raw product. Feeding strategy was not found to be the dominant explainer of ammonia-N losses. These three interventions are considered together.

Ammonia originates in the nitrogen part of faeces and urine. Thus, a potential method to decrease ammonia emissions is to reduce nitrogen residues in manure by appropriate feed rations. Nahm et al. (2002) reported an early critical review into this topic, estimating 60% emission reduction in one particular case, but noted that expert intervention and support would be needed.

There is a wide literature across different animals and feeding strategy types, though fewer with measurements and a focus on ammonia compared to greenhouse gases. The extent of greenhouse gas and ammonia emissions vary considerably across different livestock production systems as they are influenced by animal type, feed, climate, soil type and management practices (Rotz et al., 2014). There is some evidence that phase feeding can reduce emissions (Magyar et al. 2021) via a reduction in N in excreta.

A meta-analysis of the effects of dietary protein concentration and degradability on milk protein yield, and efficiency of utilisation of dietary N for milk protein synthesis, concluded that the Crude Protein (CP) concentration of the diet is the most important dietary factor influencing milk N efficiency, and that reducing dietary CP is the most significant means to increase efficiency of dietary protein utilisation (Huhtanen and Hristov, 2009).

The practical effect of reducing crude protein was shown for dairy cows fed a 14% CP diet. The cows excreted 45% more urinary N for a 19% CP diet compared with excretion from cows fed a 14% CP diet (Misselbrook et al., 2005a). There was also a small decrease in faeces N at the lower CP diet.

The difficulty in quantifying the mitigation from diet change is that although specific experiments have shown quantified emission reductions, current protein evaluation systems are unable to predict marginal urinary N output in response to changes in diet composition (Dijksta et al, 2013). This makes it difficult to standardise efficiency factors linked to CP.

3.4.1.1 Causality

There is both measurement and modelling evidence that management of protein and lipid intake reduces ammonia emissions (Le Dinh et al., 2022; Hansen et al, 2014). In many studies, ammonia emissions are measured in vitro or measured above the manure pit rather than ammonia emissions from animal houses. There are a wide range of feeding strategies, specific general recommendations rather than general advice mean that causality is not a simple evidence stream.

In addition, separating feed strategy effects from management systems (extensive or intensive) and climate/farming system variables make confidence in specific reduction factors difficult. Evidence is primarily focussed on the pig and beef sector. There is evidence of both manipulating dietary CP and phase feeding. Van Emous et al. (2019) showed a 9% decrease in ammonia for broiler breeders under such a regime. (**AMBER**)

3.4.1.2 Co-Benefits and Trade-offs

Feeding strategies for ammonia emission reduction have also been assessed for positively abating nitrous oxide emissions (Sanchez-Martin et al. 2017). Reduction in crude protein (CP) diets can reduce need for supplements in feed and reduction of other costs (Abassi et al. 2018).

[TOCB Report-3-2 *GHG* **ECPW-145**] The most obvious benefit of optimising livestock feeding systems to match animal requirements is the improved nutrient use efficiency, improved environmental footprint, and improved profit margins. This extends to drivers of whole farm efficiency such as reduced disease, lower replacement rates, improved fertility, improved age at first calving etc.

Overall, these strategies have the potential to result in much more efficient production systems. Trade-offs occur through the requirement to spend additional management time on diet planning and monitoring of performance but have benefit for air and water quality.

[TOCB Report-3-2 *GHG* **ECCM-069**] A number of benefits are associated with the correct management of protein and starch in the diet. These include reduced cost of ration formulation, improved animal growth rates, reduced ill-health due to dietary imbalance, reduced nitrogen wastage (though urine and manure). These will have significant benefit for water quality. There are no significant trade-offs, other than the potential for reduction of animal performance if protein supply is reduced too far.

3.4.1.3 Magnitude

Reductions up to 30% ammonia emission have been reported in the literature however high variability would be expected given the diverse approaches to managing feeding strategies and range of livestock.

3.4.1.4 Timescale

Adjustment of feed can be implemented within the production cycle. However, evidencing the mitigation would not be easily verifiable as would be a specific causal link to the feed within a non-research farm environment.

3.4.1.5 Spatial Issues

Local to animal housing

3.4.1.6 Displacement

The evidence does not indicate pollution displacement.

3.4.1.7 Maintenance and Longevity

Modified, lower protein diets may be sustainable and economic. Other approaches which involved synthesis of feed additives would be an added cost and may not be sustainable. Concerns on welfare and health of animals with some diets, whereas ad-lib feeding has been associated with better pig health (Hansen et al. 2014).

3.4.1.8 Climate Adaptation or Mitigation

Reduced excretion of N in urine and faeces can reduce nitrous oxide emissions in soils – depending on soil and weather conditions.

3.4.1.9 Climate Factors / Constraints

Not assessed

3.4.1.10 Benefits and Trade-offs to Farmer/Land-manager

Benefits of lower protein feeding strategies can be decreased economic costs, however proprietary feed additives may add costs (e.g. lipids, amino acids).

3.4.1.11 Uptake

Not assessed

3.4.1.12 Other Notes

None

3.4.2 AQ-01: Free range poultry/pigs in woodland

Silvopastoral systems whereby animals are free range within wooded or scrub areas. It has been noted that in different parts of Europe what people consider as modern agroforestry in one location, may be considered as common practice in another (Burgess and Rosati, 2018). Perks et al. (2018) reviewed the potential of agroforestry in Scotland and noted that though the primarily target benefit was carbon management, Bealey et al. (2015, 2016) had modelled potential reductions in diffuse air pollution.

3.4.2.1 Causality

There is limited evidence for reduction of ammonia emissions, $PM_{2.5}$ or air pollutants by free range poultry and pigs in woodland **(AMBER)**, however the effect would be consistent with the evidence logic chain. Bealey et al. (2016). Bealey et al. (2016) focussed on a range of planting strategies showed that woodlands designed to recapture ammonia from a range of livestock sources could recapture a substantially greater fraction of ammonia emissions, in the range 20% to 40%, the latter representing housing of poultry under a woodland canopy.

3.4.2.2 Co-Benefits and Trade-offs

Recent reviews include Riber et al (2018).

3.4.2.3 Magnitude

The magnitude is primarily modelled rather than measured. In ideal circumstances reductions in the range 20-40%. However, validation is required.

3.4.2.4 Timescale

The timescale would strongly depend on the economics and motivation of the industry. For example, the growth in the woodland egg commercial sector in the past 20 year shows a rapid diversification of practice (Jones et al. 2007; Stadig et al 2017).

3.4.2.5 Spatial Issues

No assessment.

3.4.2.6 Displacement

The chemicals diverted from air pollution emissions (ammonia, $PM_{2.5}$ and other gases) will pass into the ecosystem.

3.4.2.7 Maintenance and Longevity

On-going maintenance costs of the condition of woodland and shelter belts is required and protection of animals.

3.4.2.8 Climate Adaptation or Mitigation

No assessment.

3.4.2.9 Climate Factors / Constraints

No assessment.

3.4.2.10 Benefits and Trade-offs to Farmer/Land-manager

Röhrig et al. (2020) noted the positive perception of some farmers that thought that the free range pigs reduced air pollution because the animals' management of grasses and weeds decreased the need for machinery. Lower stocking rates were also considered a benefit by one farmer, perceiving a reduction in physical soil disturbance. Better management of wildfires was considered another benefit of animals grazing or browsing in woodlands by one farmer. However, the evidence is currently primarily anecdotal.

3.4.2.11 Uptake

Significant uptake in poultry with access to trees has occurred, with much more limited uptake in other sectors.

3.4.2.12 Other Notes

None

3.4.3 ECAR-020: Extending cattle grazing season

Air pollution emissions from cattle are much less when they are grazing than when they are housed. For ammonia, this is due to the urine excreted during grazing rapidly infiltrating the soil whereas indoors remains on the surface of impermeable floors and yards, therefore there are direct benefits from extending the grazing season (Webb et al. 2005) and a significant amount of research has been carried out primarily around future climate change, and how that affects agricultural welfare, economics and greenhouse gas mitigation (Hennessy and Kennedy 2009, Hennessy et al., 2020, Wreford and Topp, 2020) and has been assessed in IPPC assessments. There is limited literature on the air pollution topic.

3.4.3.1 Causality

Webb et al. (2005) undertook an early desk study using an additional 2 week grazing period per annum and estimated a reduction of ~10% of ammonia emissions, with the primary fate of the waste nitrogen being lost as aqueous phase nitrate. Voglmeier (2018) studied in the field and found that ammonia emissions were reduced via grazing compared to housing and this is in line with other studies.

3.4.3.2 Co-Benefits and Trade-offs

[TOCB Report-3-5B *Grassland* **ECAR-020**] Significant risk of deterioration through over-grazing or inappropriately timed grazing of species-rich grasslands and other grazed semi-natural habitats. Risk to wild pollinators, other insects and their predators if grazing legume and herb rich swards prevents flowering.

[TOCB Report-3-6 *Carbon* **ECAR-020**] Extension of the grazing season will increase the likelihood that grazing occurs in wet conditions where soil compaction and erosion are more likely. This is associated with a decrease in above and below ground soil carbon sequestration (see carbon sequestration review, Report-3-6 *Carbon*, section 3.12.1.0). There is also evidence that nitrous oxide emissions increase when soils are wet and poorly drained (Cardenas et al. 2017). For wider effects of grazing intensity on carbon sequestration see section 3.11.3.0 of the carbon sequestration review. Extending the grazing season may reduce the need for feedstock production elsewhere, but the magnitude of this effect is unknown.

Food and fibre production	Area under production or yield and outside of ELM	L*
Global, regional & local climate regulation	Above ground carbon sequestration	T*
	Below ground carbon sequestration	T*

Duplicate evidence base: **ETPW-106** Manage timing of grazing and select livestock type to allow flowering and seed return, and control competitive and invasive species.

3.4.3.3 Magnitude

Potentially large impact for ammonia emission reduction, however limited measurement evidence and tradeoffs important. Voglmeier (2018) noted that the major source of ammonia emission from improved grassland was from fertiliser additions to maintain grass quality.

3.4.3.4 Timescale

Annual.

3.4.3.5 Spatial Issues

Regional variation depending on land type, drainage and climate.

3.4.3.6 Displacement

Reduced air emissions result in increased nitrate in soils. Limited evidence for an increase in nitrous oxide emissions, however measurements show lower than models predict.

3.4.3.7 Maintenance and Longevity

Sustainable pasture maintenance required.

3.4.3.8 Climate Adaptation or Mitigation

Climate scenarios indicate that in some regions of Europe longer grazing seasons are likely. Phelan et al. (2015) Extrapolating these relationships to future climate change scenarios, most European countries were predicted to have a net increase in GSL with the increase being largest (up to 2.5 months) in the north-east of Europe.

3.4.3.9 Climate Factors / Constraints

Regional variation depending on land type, drainage and climate.

3.4.3.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment.

3.4.3.11 Uptake

No assessment.

3.4.3.12 Other Notes

None

3.4.4 ECCM-008: Use improved livestock housing management

E.g. regular slurry scraping, washing down floors and yards, using electric or robotic scrapers; and store scrapings appropriately where business is not regulated under IED.

This action has also been covered above and has well tested evidence with outcomes consistent with the evidence chain (GREEN).

3.4.5 ECAR-026: Use improved livestock flooring

E.g. slatted flooring and grooved floors or stand-off pads woodchip for over wintering cattle as an alternative to slurry-based housing.

Improving livestock flooring systems typically involves changes from a solid to slatted or permeable floor under which urine and faeces can be collected and either manually or automatically removed. Flooring products are available on the market for cattle, pigs and poultry. Dutch Ammonia and Livestock Farming regulations have official assessments on products indicating ammonia emission reduction potential (usually presented in ammonia emissions in kg ammonia per year per animal. This option is available within the Countryside Stewardship grants[4]. However, the relative efficacy of available technologies and strategies to reduce nitrogen emissions and improve NUE, whether concerning single or multiple N_r species or supply chain activities, remains unclear, as do their comparative technical and economic feasibility currently in the UK.

The Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) (Giner Santonja et al (2017) describes existing and emerging technologies for reducing emissions using improved flooring systems – including recently report methods using neutral pH polymeric flooring layers (Boggia et al. 2019). Qu et al (2021) undertook a meta-analysis of the effects of housing systems, measurement methods and environmental factors. They found issues with the emission measurement approaches and the duration of experiments. They reported for both ammonia and methane emissions in a meta-analysis, differences between solid floor, slatted floor, flushed and scraped systems were difficult to separate as environmental factors (climate, internal temperature, other farm management activity) had more pronounced effects in many locations. The strong recommendation would be that building ventilation systems evidence and more detailed emission studies to reduce environmental effects would be needed to clearly verify differences. Qu et al. (2021) indicated need for standardised measurement methods for gas emission rates to reduce large variability and uncertainty across studies.

3.4.5.1 Causality

There is clear modelled and limited direct evidence of using improved flooring systems for reducing ammonia emissions though it is noted Qu et al. (2021) reported low influence of emissions on flooring and more on ambient environmental conditions – though the two factors are not completely independent either. (AMBER)

3.4.5.2 Co-Benefits and Trade-offs

Greenhouse gas emissions also co-vary with the management of waste and flooring; however, many studies have variable results. A trade-off which has been raised in the literature between reducing emissions and animal welfare (e.g. Adler et al. 2020), however mitigation with different types of flooring is an area of on-going development.

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[4] www.gov.uk/countryside-stewardship-grants/aq2-low-ammonia-emission-flooring-for-livestock-buildings; published Feb 2021

3.4.5.3 Magnitude

Highly variable: up to 50% reduction of ammonia emissions to no discernible effect.

3.4.5.4 Timescale

Agricultural housing cycles; many flooring types require infrastructure change to adapt, therefore it is general a lead time.

3.4.5.5 Spatial Issues

None

3.4.5.6 Displacement

Reduction of emissions requires on-going management of wastes once collected.

3.4.5.7 Maintenance and Longevity

All systems would requirement maintenance. Recent review by Galama et al. (2020) reviews the different types of housing and the logistics and environmental considerations.

3.4.5.8 Climate Adaptation or Mitigation

Climate and ventilation are key factors which also influence the emission reductions achievable by floor type.

3.4.5.9 Climate Factors / Constraints

No assessment.

3.4.5.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment.

3.4.5.11 Uptake

No assessment.

3.4.5.12 Other Notes

As there is such a wide range of interventions and types of flooring across agricultural sectors, this action would need clear specifications and evidence for methods.

3.4.6 ECAR-027: Use improved livestock housing+ infrastructure to reduce emissions *(Livestock management – housing and handling)*

E.g. ammonia scrubbers and biotrickling filters to mechanically ventilate housing unless regulated.

Research efforts have been made toward recovering nitrogen from raw as well as digested livestock manures over the last decade. Many novel technologies as well as ones that have already been implemented to recover nitrogen from municipal wastewaters have been studied for their use in the livestock sector.

Pandey and Chen (2021) reviewed available technologies for recovering housing air emissions and manure nitrogen. Removal of reactive nitrogen would address removal of ammonia reduction of $PM_{2.5}$ and removal of other reactive nitrogen gas pollutants including nitric acid and nitrous acid. For livestock housing these technologies are more at the innovation end of the scale in the UK livestock housing sector rather than being routinely implemented therefore there are many approaches reported in the literature, with very few independent emission reduction studies from long-term working buildings. However, gas-permeable membranes, air stripping and vacuum thermal stripping are viable options. Scrubbers and biofilters are extremely common and well tested in other industries (including livestock processing/rendering). Use of infrastructure systems for pollutant removal often stems from a requirement for odour abatement and they work well (very well in the case of scrubbers) to reduce ammonia emissions (see Fletcher et al. 2014)

It is noted that air treatment systems while preventing the environmental costs incur direct economic costs. Specifically, these can be categorised as financial (e.g. capital and running costs), ecologic (energy consumption, chemical use, discharge water), and technical (operations and performance).

3.4.6.1 Causality

There is a direct link between removal of a pollutant from the air and a reduction of atmospheric emissions, however it is not a well-tested intervention. (AMBER) Banhazi (2018) reported a 90% reduction of ammonia concentrations after a biotrickling filter. Reductions of ammonia by permeable membranes range between 56-100% (Pandey and Chen, 2021) across a range of poultry, swine and vegetable wastes. Water air scrubber systems are not particularly effective but acid scrubbers can be more efficient e.g. Ashtari et al. (2016) reported an average ammonia removal efficiency of 49% at pH8 and 84% from ammonia-air mixture at pH2.

Reverse osmosis is the movement of solvent opposite to that in the osmosis process, where a solvent is forced from a concentrated solution to a dilute solution through a semi-permeable membrane by applying a pressure greater than the osmotic pressure and manure total ammoniacal nitrogen removal studies have demonstrated total ammoniacal nitrogen removal percentages of >90% (Pandey and Chen, 2021). Most research has been limited, small-scale and not operated long-term. Therefore, it is not clear yet the economics and performance of long-term operations, however it is noted that the wastewater industry operates similar techniques successfully.

3.4.6.2 Co-Benefits and Trade-offs

No assessment.

3.4.6.3 Magnitude

If implemented the reduction of air pollution emissions would be large.

3.4.6.4 Timescale

These actions require a sector-wide strategy to implement therefore this is a medium-term approach.

3.4.6.5 Spatial Issues

Removes pollution at source in housing.

3.4.6.6 Displacement

Management of stripped TAN or ammonium need to be managed such that the reactive nitrogen is not released elsewhere

3.4.6.7 Maintenance and Longevity

All systems for air pollutant removal with livestock housing infrastructure will require skilled maintenance and on-going investment.

3.4.6.8 Climate Adaptation or Mitigation

No issues.

3.4.6.9 Climate Factors / Constraints

No issues.

3.4.6.10 Benefits and Trade-offs to Farmer/Land-manager

The benefits would only be realised if the economics of the intervention were managed.

3.4.6.11 Uptake

Low uptake currently. Would require sector wide policy intervention.

3.4.6.12 Other Notes

n/a

3.4.7 AQ-02: Monitor air quality pollution and greenhouse gas footprint of agricultural buildings to actively manage emissions *(Livestock management – housing and handling)*

Knowledge of the external air pollution levels around agricultural buildings in order to quantify the emissions via model or calculation allows direct knowledge of the pollutant issue of a specific site or type of housing. Mass flow models can be used to understand emissions (e.g. Webb and Misselbrook 2004). Additionally, if the AQ or GREENHOUSE GAS footprint approach shows high temporal resolution the specific activities within and around the agricultural buildings can be identified as hot spots or leaks and remediation action implemented. However, to obtain high accuracy emissions data can be challenging (Casey et al. 2012) however approaches are being developed which if invested in would bring down the investment cost and make the capability more routinely available (Zheng et al. 2016).

3.4.7.1 Causality

There is limited evidence of examples of where pollution sources have been identified by measurement and subsequently reduced in the agricultural industry, however in the wider air quality context, particularly in oil, power generation and automotive industries, measurement and identification of sources for targeting emission reduction is reasonably normal. (AMBER) There are long term background monitoring and occasional campaigns/regulator measurements to assess air pollution impacts of ammonia from specific sources.

3.4.7.2 Co-Benefits and Trade-offs

Methodology once developed and evidence obtained can be generally applicable.

3.4.7.3 Magnitude

Unknown.

3.4.7.4 Timescale

Medium term.

3.4.7.5 Spatial Issues

Monitoring closer to sources gives better confidence in source apportionment; more distal measurements allow more sources to be considered.

3.4.7.6 Displacement

Not applicable.

3.4.7.7 Maintenance and Longevity

Low-cost samplers and equipment do not need significant maintenance. Analysers require expert use and maintenance.

3.4.7.8 Climate Adaptation or Mitigation

Not applicable.

3.4.7.9 Climate Factors / Constraints

Seasonal variations as well as the agricultural cycles need to be taken into account in any monitoring.

3.4.7.10 Benefits and Trade-offs to Farmer/Land-manager

Direct knowledge of the problem and a tangible change when a mitigation action taken. Potentially usable are evidence for programmes where payment for implementation part of the scheme.

3.4.7.11 Uptake

Where economically feasible farmers and industry have been keen to collaborate on monitoring as it is a direct understanding of issues (e.g. Vogt et al. 2013; Bell et al. 2016).

3.4.7.12 Other Notes

None

3.4.8 AQ-03: Monitor indoor concentrations of ammonia and GREENHOUSE GAS *(Livestock management – housing and handling)*

Historically indoor ammonia concentration in agricultural housing has been measured for human health purposes in workplace exposure limits. In addition, for animal welfare purposes air pollution has been measured (Ni et al. 2021). The major known gases include ammonia, hydrogen sulphide, carbon dioxide, methane, and nitrous oxide, VOCs including odours and other compounds include particles such as dust and bioaerosols.

Methods are available for indoor concentration measurements (e.g. summarised in this review of swine housing: Ni et al. (2018) and sensor systems are being continuously developed as technologies mature (Zeng et al. 2021) the approach becomes more accessible.

Greenhouse gases can be measured with either handheld instruments or open path analysers. There is indicative evidence that indoor measurement concentrations can inform choices and there are commercial and regulatory information packages available[5], however currently under COGAP there is no measurement standards advice. Measurements are needed though to inform and assess actions both at the instantaneous operation level (informing instant control) and to inform longer-term and evidence change. Long-term monitoring in exemplar housing systems would be beneficial and cascade standards for short term assessments.

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[5] e.g. www.alltech.com/blog/how-control-ammonia-levels-poultry-houses

3.4.8.1 Causality

Indicative currently however in theory if air pollution concentration measured then change and progress can support reduction actions. (AMBER)

3.4.8.2 Co-Benefits and Trade-offs

Co-measurement of carbon dioxide and methane can support actions to reduce carbon footprint.

3.4.8.3 Magnitude

Unknown.

3.4.8.4 Timescale

Medium term.

3.4.8.5 Spatial Issues

Location/system specific.

3.4.8.6 Displacement

As with all air pollution reduction actions, the reactive nitrogen conservation is a priority to reduce loss to the environment.

3.4.8.7 Maintenance and Longevity

Sensors require regular calibration and maintenance.

3.4.8.8 Climate Adaptation or Mitigation

No assessment.

3.4.8.9 Climate Factors / Constraints

No assessment.

3.4.8.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment.

3.4.8.11 Uptake

No assessment.

3.4.8.12 Other Notes

None

3.5 BUNDLE: RESTORATION, MANAGEMENT AND ENHANCEMENT

Restoration, Management & Enhancement - Grassland
ECAR-035: Reduce stocking density or remove livestock grazing where likely impacts on sensitive habitats and species (aquatic and terrestrial)
Restoration, Management & Enhancement - Hedgerows

ECCM-080: Enhance/ manage hedgerows around point-source polluters
Restoration, Management & Enhancement – Woodland and Woody Features
EBHE-196: Planted Ancient Woodland (PAWS) restoration
EBHE-198: Restore/ manage ancient woodland with native broadleaf species
ECAR-033EM: Enhance/ manage shelter belts (tree, woodland, scrub, and hedgerow) with appropriate species composition near sensitive habitats
ECPW-156M: Enhance/ manage trees and shrubs around point-source polluters
EBHE-205EM: Enhance/ manage wood pasture (e.g. through appropriate grazing)

3.5.1 ECAR-035: Reduce stocking density or remove livestock grazing where likely impacts on sensitive habitats and species (aquatic and terrestrial)

Lowering stock density or removing livestock would directly reduce ammonia emissions to the air. The caveat being that if overall stocking levels were maintained then there would be no difference to the emission of ammonia to the air and hence minimal impact on the $PM_{2.5}$ reduction also at a regional or national scale.

3.5.1.1 Causality

Removal of individual sources of ammonia reduces emissions. (GREEN) and hence would lower ammonia and $PM_{2.5}$ concentrations.

3.5.1.2 Co-Benefits and Trade-offs

No assessment.

3.5.1.3 Magnitude

The magnitude would be proportionate the reduction in number of animals.

3.5.1.4 Timescale

Immediate.

3.5.1.5 Spatial Issues

If only a local reduction of animal numbers, then the effect would be local.

3.5.1.6 Displacement

If higher stocking densities were located elsewhere then the emissions would be displaced. The local protective value of lower ammonia and $PM_{2.5}$ would be offset in other locations.

3.5.1.7 Maintenance and Longevity

n/a

3.5.1.8 Climate Adaptation or Mitigation

n/a

3.5.1.9 Climate Factors / Constraints

In a warming climate, increasingly lower stocking densities would be needed to achieve the same results

3.5.1.10 Benefits and Trade-offs to Farmer/Land-manager

Fewer animals would lower farm income. Geographic issues may be incurred if whole farm fields are close to sensitive ecosystems. Stocking density also impacts pasture maintenance, soil compaction and other farm management issues.

3.5.1.11 Uptake

No assessment.

3.5.1.12 Other notes

None

3.5.2 ECCM-080EM : Enhance/ manage hedgerows around point-source polluters

See also above.

3.5.3 EBHE-196: Planted Ancient Woodland (PAWS) restoration and EBHE-198: Restore/ manage ancient woodland with native broadleaf species

PAWS are ancient woodland sites where the semi-natural woodland has been replaced with a plantation. The sub-set of most relevance are those sites planted with non-native species since 1930. A substantial proportion of PAWS are either under restoration or likely to be restored over the next 20-30 years back to the ancient woodland which can either be native coniferous or native broadleaf species. Semi-natural woodland is more porous than standard conifer plantation. Air flow through and air pollution removal by trees and woodlands requires the trees not to act as a solid barrier (which primarily disperses pollution to higher altitudes in the atmosphere). In a review of urban vegetation potential for pollution removal Nemitz et al. (2020) identified that action to have a significant effect would have to be at large scale and there were other disbenefits (e.g. biogenic volatile organic compound gas emissions and secondary air pollutant ozone formation potential). However, where a national and regional approach is taken there is potential for reduction of ammonia concentration in air (Bealey et al. 2015) and spatially targeted approaches to reduce air pollution are proposed (e.g. Carnell et al. 2017).

3.5.3.1 Causality

Additional woodland which supported wind flow through the trees would remove ammonia and hence lower $PM_{2.5}$ (GREEN). However, given the major driver for PAWS restoration is not air pollution removal the restoration is not likely to be designed to maximise the removal of air pollution therefore the effect would likely have minimal benefit.

3.5.3.2 Co-Benefits and Trade-offs

No assessment.

3.5.3.3 Magnitude

Small.

3.5.3.4 Timescale

Decadal.

3.5.3.5 Spatial Issues

PAWS and source regions are not necessarily co-located.

3.5.3.6 Displacement

Not applicable.

3.5.3.7 Maintenance and Longevity

All woodland requires long term management.

3.5.3.8 Climate Adaptation or Mitigation

Not relevant.

3.5.3.9 Climate Factors / Constraints

Not relevant.

3.5.3.10 Benefits and Trade-offs to Farmer/Land-manager

Assessed elsewhere.

3.5.3.11 Uptake

No assessment.

3.5.4 ECPW-156M: Enhance/ manage trees and shrubs around point-source polluters and EBHE-205EM: Enhance/ manage wood pasture (e.g. through appropriate grazing)

No assessment.

3.6 BUNDLE: SOIL MANAGEMENT AND PROTECTION

Soil Management and Protection: Fertiliser, nutrient, manure and mulch management

This bundle covers actions involving soil management and protection, especially inputs to the soil including different types of fertilisers and nutrients as well as storage of slurry and manure. In total, this bundle covers 35 actions that have been grouped to discuss similar types of inputs such as slurry or chemical fertilisers together. As ammonia is a precursor to $PM_{2.5}$, using agricultural systems that reduce soil ammonia emissions could decrease surface secondary inorganic aerosol ($PM_{2.5}$) formation (Bauer et al. 2016). Hence, actions discussed to reduce ammonia emissions will by association also reduce concentrations of $PM_{2.5}$. None of the actions discussed here will actively remove other air pollutants although some emissions may be avoided as a result of implementing certain actions.

3.6.1 ETPW-239: Increase production from grass grazing and forage and reduce compound feed to reduce nutrient inputs

3.6.1.1 Causality

Optimising the production of high-quality grass can reduce reliance on compound feed and result in both economic and environmental benefits (AFBI, 2021). More efficient livestock production feeds and feeding systems can include grazing leys sown with specific forage species and cultivars that are managed to optimise the efficiency of use of feed resources, or areas of longer-term pastures that are managed to improve their nutritional characteristics (Moorby and Fraser, 2021). However, evidence of reduced nutrient inputs due to different grazing and foraging regimes having direct impact on reducing ammonia and fine $PM_{2.5}$ is lacking and likely depends on the exact type of fodder and soil and grass type, etc.; therefore is very context dependent. Adoption of new feeds and forages should be the focus of new research (Moorby and Fraser, 2021).

3.6.1.2 Co-Benefits and Trade-offs

Different types of grazing and fodder, likely also impact on greenhouse gas emissions (e.g. methane from ruminants) (Moorby and Fraser 2021).

[TOCB Report-3-5D *Systems* **ETPW-239**] It is not clear how this would be achieved, as an increase in production from grass implies either more land under grass or more intensive grass production, albeit with reduced displacement of these production needs to locations that produce the compound feed. Local negatives for biodiversity would be expected, but potentially compensated for by positives elsewhere.

3.6.1.3 Magnitude

Too uncertain to say.

3.6.1.4 Timescale

Too uncertain to say.

3.6.1.5 Spatial Issues

Likely different according to soil type, management, etc. (Moorby and Fraser 2021)

3.6.1.6 Displacement

None as intensifying already existing grassland.

3.6.1.7 Maintenance and Longevity

Needs monitoring, ideally with measurements of nutrients in fodder and soil and resulting ammonia emissions.

3.6.1.8 Climate Adaptation or Mitigation

Forage-based livestock systems will have to adapt to a changing climate and the impacts that this will have on their primary feedstuffs (Moorby and Fraser 2021)

3.6.1.9 Climate Factors / Constraints

More efficient livestock production feeds and feeding systems can offer ways to minimise climate change but more research needed (Moorby and Fraser 2021)

3.6.1.10 Benefits and Trade-offs to Farmer/L-and manager

Could have economic benefits if less compound feed needed (AFBI, 2021).

3.6.1.11 Uptake

If proven solutions available, uptake likely as also cost saving to farmers (AFBI, 2021).

3.6.1.12 Other Notes

n/a

3.6.2 ECAR-001: ECPW-123: ECAR-004: ECAR-034: ECPW-131: ECPW-134: ECPW-136: ECPW-137: ECAR-006: ECPW-133: ECPW-227: ECCM-010 (and ECCM-011):

ECAR-001: Cover slurry, sludge, and digestate stores where business is not regulated under IED,
ECPW-123: Install/ maintain roofing over livestock yards, manure, slurry and silage stores
ECAR-004: Increase the capacity of farm slurry and manure stores to improve timing of slurry applications
ECAR-034: Locate new slurry storage away from sensitive habitats
ECPW-131: Separate slurry and digestate (liquid and solid) and store separately
ECPW-134: Store solid manure heaps on an impermeable base and collect effluent
ECPW-136: Utilise slurry / organic waste for biogas production
ECPW-137: Export manure and slurry
ECAR-006: Dilute slurry to improve soil infiltration, coupled with irrigation
ECPW-133: Cool slurries on farms where business is not regulated under IED
ECPW-227: Avoid slurry injection where there is a high risk of leaching or losses to groundwater (e.g. cracked soils)
ECCM-010 and **ECCM-011**: Acidify slurry and digestate during spreading where business is not regulated under IED

Slurry management forms a major part of the waste disposal process on farms and it is where the losses to the environment can readily occur. Slurry management is covered in the COGAP advice for minimising ammonia emissions to the atmosphere and the actions from location, movement, storage, processing and disposal (i.e. spreading) of slurry and slurry digestate are considered in this section. Need to differentiate slurry-based systems used for dairy cattle and pig farms mainly, from beef farms which still use solid waste (traditional farmyard manure) which is left in sheds until springtime or is cleaned out and stored in heaps on yards or fields.

3.6.2.1 Causality

Emissions from slurry storage is an important source that has been reported to account for approximately 10% of total livestock emissions in some countries (VanderZaag et al. 2008). Covering of stores has been proven to be efficient in reducing ammonia emissions for slurry storage which has been well documented as summarised in a recent review Kupper et al. (2020). In another recent review, ammonia emissions from slurry storage have been reported to vary by several orders of magnitude, specifically ammonia-nitrogen losses from slurry storage varied from 6% to 30% of total nitrogen in stored slurry Qu and Zhang (2021). Ammonia emissions are highly related to slurry pH. Lowering slurry pH significantly reduced ammonia–nitrogen losses Qu and Zhang (2021). Acidification was found to be efficient in reducing the emissions of ammonia solid-liquid separation causes higher losses for ammonia, anaerobic digestion promoted ammonia emissions in most studies Kupper et al. (2021). It is essential to consider the context of good management practices along the whole manure management chain when the effect of slurry treatments on emissions from slurry storage is assessed. All storage cover types reduce emissions of ammonia and overall, coverage of slurry is efficient to abate ammonia emissions involving a minimum risk of pollution swapping (Kupper et al. 2021)

The result of a recent meta-analysis showed that for the treatment, storage, and application stages, only slurry acidification as a solution was effective for the reduction of ammonia emissions (−69%), and at the same time had no pollution swapping effect with other greenhouse gases, like nitrous oxide (−21%), methane (−86%), and carbon dioxide (−15%). All other management strategies, like biological treatment, separation strategies, different storage types, the concealing of the liquid slurry with different materials, and variable field applications were effective to varying degrees for the abatement of ammonia emission, but also resulted in the increased emission of at least one other greenhouse gas (see trade-off) Emmerling et al. 2020).

It has been reported that ammonia-N concentration, nitrogen content and pH were higher in both anaerobic digestion (AD) and anaerobic digestion with solid-liquid separation and storage of the liquid fraction (ADL) storages compared to the separated liquid (SL) alone and raw manure storage (RM) Baldé et al. (2018). Annual ammonia emissions scaled by surface area from ADL (5.6 kg m^{-2} y^{-1}) were reported to be 55% higher than digestion without separation (AD), 3.5× higher than SL, and 5.6× higher than untreated RM storage. Total ammonia emissions at a facility-scale, however, were higher from storages with greater manure storage capacity (and greater surface area), resulting in the SL storage having the lowest emissions Baldé et al. (2018). This highlights that all the actions are context dependent and that more information/research is needed.

In a Mediterranean context, shallow injection of slurry effectively abated ammonia comparing to surface application (Sanz-Cobena, 2019) (Sanz-Cobena et al., 2019). In this case-study, compared with surface application of slurry, shallow injection effectively and significantly decreased ammonia losses independently of weather conditions, but reductions of ammonia emission were greater after heavy rainfall. However, this will be context dependent and due to only limited studies available, more research is needed.

For some actions covered under this bundle, such as storing manure heaps on impermeable bases and export manure and slurry, as well as diluting slurry and avoiding injections, the impact is very context dependent with limited evidence that the actions will be effective reflected in amber scoring in the spreadsheet.

The above-mentioned actions are primarily to target reduction of ammonia emissions. However, as ammonia is a precursor for fine particulate matter ($PM_{2.5}$), taking reduction of ammonia emission into consideration for $PM_{2.5}$ pollution control is therefore critical Gu et al. (2021). Hence, all measures that reduce ammonia emissions from agriculture will by association also reduce concentrations of $PM_{2.5}$.

3.6.2.2 Co-Benefits and Trade-offs

All actions have trade-offs with greenhouse gas emissions, especially nitrous oxide and methane (Kupper et al. 2020). Odour reduction of VOCs with no other air quality impacts can be an additional co-benefit.

[TOCB Report-3-5B *Croplands* **ECAR-004**] Assuming this action leads to timing of slurry applications to avoid run-off into surfaces waters there is potential for indirect benefits to aquatic habitats and species of reducing the risk of pollution, but the extent of this benefit is likely to depend on the proportion of livestock farms in the sub-catchment that take up this action.

[TOCB Report-3-2 *GHG* **ECPW-137**] Benefits of exporting manure and slurry include the reduction of GHG to the atmosphere and excess nutrients to water, provided that the slurry is exported to an area which can make more effective use of it. The export of surplus nutrients to an appropriate region will optimise nutrient use, displace chemical fertilisers, and decrease the environmental impact. In addition to greenhouse gas reductions, other benefits around reduction of nutrient loading of land will accrue. Based on average values of N content of raw slurry at 7% DM, the export of 500 t of raw slurry off farm with a P_2O_5 content of 300 kg. If the same amount of N is exported in separated slurry solids, 189 t of solids would have to be exported containing 378 kg of P_2O_5 (Lyons et al., 2021). If, however, the slurry is moved to an area which cannot make more effective use of it than the farm of origin, benefits will be seen locally to the farm of origin, but negative impacts are likely locally to the receiving farm. Trade-offs centre around the cost of storage and transport of excess nutrients, as well as the risk of spillage during transport.

[TOCB Report-3-2 *GHG* **ECPW-131**] Co-benefits of slurry separation include improved nutrient management and resource utilisation efficiency, as well as more targeted spatial application. Trade-offs centre around the cost of the system and the long-term nature of payback.

[TOCB Report-3-4 *Water* **ECPW-137**] Crop available nutrient supply from the manures will reduce the need for manufactured fertiliser inputs to meet optimum crop requirements on the receiving farm. On arable soils, the addition of organic matter from the manures has the potential to improve soil quality. Manure storage and application equipment will be required on the receiving farm to ensure manure applications are made at appropriate timings and rates.

[TOCB Report-3-2 *GHG* **ECAR-006**] Benefits of diluting slurry include the reduction of GHG emissions to the atmosphere and reduced run-off to water systems. Trade-offs centre around the cost of infrastructure and capacity to facilitate dilution. Overall, this strategy has the potential to result in much more efficient nutrient management with benefit for air and water quality. Diluted slurry could increase risks of water pollution if not injected into soil.

[TOCB Report-3-2 *GHG* **ECAR-004**] Benefits of increased capacity for slurry and manure to improve timing of application include the reduction of loss of methane and ammonia into the air, reduction of Nitrous Oxide under cold conditions and the retention of additional nitrogen within manures which increases the value of slurry. Trade-offs centre around the cost of storage, and the long-term nature of payback. Overall, this strategy has the potential to result in much more efficient nutrient management with benefit for air and water quality.

3.6.2.3 Magnitude

One study reports that from treatment, storage, and application stages, only slurry acidification was effective for the reduction of ammonia emissions without resulting in pollution swapping, resulting in a reduction of 69% (Emmerling et al. 2020). In Denmark, acidification of slurry has come into commercial use for treating 20% of slurries. Research in several countries has demonstrated that the injection and incorporation of slurry, compared with surface broadcast application, can reduce ammonia volatilisation by up to 90% due to the reduction in the contact surface between the atmosphere and the ammonium-nitrogen applied with the manure Sanz-Cobena et al. (2019). However, limited data is available so generalisation should be avoided.

3.6.2.4 Timescale

Slurry cover has an instant effect in reducing ammonia emissions.

3.6.2.5 Spatial Issues

These are all very localised (farm-scale) actions.

3.6.2.6 Displacement

Export of slurry and manure [**ECPW-137**] will likely result in displacement.

3.6.2.7 Maintenance and Longevity

Covering slurry and maintaining roofing would result in longevity of the actions.

3.6.2.8 Climate Adaptation or Mitigation

Higher temperatures will increase ammonia emissions. Acidification can reduce methane emissions.

3.6.2.9 Climate Factors / Constraints

Higher temperatures will increase ammonia emissions.

3.6.2.10 Benefits and Trade-offs to Farmer/Land manager

Benefits of being able to adjust timing of slurry applications in storage facilities available, therefore potential to save costs for chemical fertilisers.

3.6.2.11 Uptake

No major barriers to uptake.

3.6.2.12 Other Notes

n/a

3.6.3 ECPW-152: ECPW-244: ECAR-028

ECPW-152: Keep poultry litter dry (through storage/covering, maintaining drinkers) and regularly removing litter using cleaning belts where not applicable under BAT environmental permitting regs.
ECPW-244: Incinerate poultry litter
ECAR-028: Use poultry litter additives to reduce pH

Poultry litter is a dominant source of ammonia emission within poultry housing. How it is managed within the livestock housing, transport, storage, alterations and spreading determines the ammonia emission rate and the final location of the nitrogen within the litter. These three actions all are part of the litter management and therefore are considered together.

3.6.3.1 Causality

The volatility rate of ammonia in poultry litter depends on the pH, humidity, ventilation rate, air velocity, manure nitrogen content, and temperature Swelum et al. (2021). It has been suggested by one study that litter humidity in poultry houses should be maintained between 15% and 25%, as higher than this, litter humidity promotes efficient ammonia release. Also, the litter's pH is a major factor regulating the volatilisation of ammonia because this determines the partitioning between the ammonium (aqueous soluble salt ion, NH_4^+) and ammonia gas ratio. However, limited evidence is available to evidence if keeping litter dry or using additives to reduce the pH would actually reduce ammonia emission (and by association $PM_{2.5}$) (**ECPW-152 AMBER; ECAR-028 AMBER**) and in particular, by how much. Incinerating poultry litter has been reported to reduce ammonia emission and therefore the poultry manure was assess as having lower acidification and eutrophication potentials even when including NO_X generation by litter incineration (Ogino et al. 2021). (**ECPW-244 AMBER**) More research is needed before generalising the magnitude of each of the actions. Most studies have been pilot scale rather than large scale.

3.6.3.2 Co-Benefits and Trade-offs

If excess not released as ammonia might result in higher NH_4 and NO_3^- that could potentially cause water pollution. Appropriately processed dried poultry manure/litter has been proposed to help in reducing the dependence on chemical fertilisers with ambitions for effective and efficient disposal of poultry waste to embed sustainability into the sector (Prabakaran and Valavan et al 2021). Poultry litter incineration for power plants has the power generation co-benefit. On the other hand, resulting bioaerosols can have adverse effects on farm worker health (Wultsch et al. 2009).

3.6.3.3 Magnitude

ECPW-152: Keeping RH low under constant temperature has been shown to lower ammonia emission rates so can be a significant reduction in emissions, however as recent studies (e.g. Rosa et al. 2021; Groenstein et al. 2019) the temperature variation in real-world housing can be confounding variables.
ECPW-244: Incinerate poultry litter: The process of incineration will oxidise ammonia to oxidised nitrogen forms which are also air pollutants.

ECAR-028: Use poultry litter additives to reduce pH: The evidence for this is highly variable outside of specific intervention studies.

3.6.3.4 Timescale

Litter drying systems are available and are used in many housing systems already. Technology is mature and rapid to fit. Incineration plants and power plants are available however there are often investment and political issues which affect timescales of implementation.

3.6.3.5 Spatial Issues

No assessment.

3.6.3.6 Displacement

Without care, incineration can replace ammonia emissions with oxidised nitrogen air pollution.

3.6.3.7 Maintenance and Longevity

All actions would require infrastructure and on-going funding to maintain.

3.6.3.8 Climate Adaptation or Mitigation

Too uncertain to say.

3.6.3.9 Climate Factors / Constraints

Too uncertain to say.

3.6.3.10 Benefits and Trade-offs to Farmer/L-and manager

Litter drying has been observed to improve animal welfare. Some pH interventions have been shown to have minimal animal health concerns (Toppel et al. 2019), however as number of types of pH interventions are large each one would need to be assessed. Bioaerosols might be of concern to farm worker health.

3.6.3.11 Uptake

Litter drying and belt systems are used widely in the UK poultry industry. Litter incineration already occurs for some of the poultry waste.

3.6.3.12 Other Notes

Poultry litter has other uses, e.g. in biodiesel and biogas production (Prabakaran and Navaran (2021)

3.6.4 ECAR-015: ECPW-110: ECPW-171: ETPW-242

ECAR-015: Replace nitrogen fertiliser application by using clover in pasture or arable cropping systems
ECPW-110: Reduce fertiliser (organic and inorganic) applications in high risk areas
ECPW-171: Use very low inputs on permanent grassland
ETPW-242: Reduce fertiliser (organic and inorganic) application to below conventional levels

Actions to reduce or replace nitrogen fertilisers are a direct way of reducing ammonia emissions to the atmosphere and hence contribute to $PM_{2.5}$ reductions also. Depending on the action taken, there is potential of avoidance of other air pollution emissions. Generally reducing fertiliser input, especially to very low levels, will reduce ammonia emissions as a certain percentage of fertiliser (organic and inorganic) is emitted as ammonia, however, it is very context dependent and limited data beyond case studies are available which makes generalising difficult. Reducing “below conventional levels” is too vague an action to assess or easily implement.

3.6.4.1 Causality

A living mulch system using nitrogen-fixing cover crops is a system in which a legume cover crop grows throughout the cash crop's growing season while contributing enough nitrogen to the soil pool to satisfy the needs of the cash crop. This has been shown to reduce fertiliser use by as much as 75% less in some field trials, however, generally the consensus is that the environmental impacts are relatively unknown **(ECAR-015 AMBER**) (Bauer et al., 2016). One study has in fact shown that living mulch plots had higher ammonia emissions than conventional treatments (Bauer et al a. 2016). A recent meta-analysis on impacts of agronomic measures on crop, soil, and environmental indicators calculated mean impacts on yield for combined and organic fertiliser (overall increase and decrease, respectively) and reported substantial uncertainty due to a range of individual effects indicating both positive and negative impacts (Young et al. 2021). Reducing fertiliser input whether in high-risk areas or onto permanent grassland, would directly reduce impact of ammonia emissions. **(ECPW-110 AMBER)** whereas it is clearer evidence that ammonia emission would decrease when very low inputs are used and can be a carbon and nitrogen sink rather than source. However, it is noted that recently evidence has been focussed on the greenhouse gas budgets rather than the ammonia budget. (**ECPW-171 GREEN)**

3.6.4.2 Co-Benefits and Trade-offs

White clover living mulch plots have been shown to also have higher greenhouse gas fluxes.

[TOCB Report-3-3 *Soils* **ETPW-242**] Nutrient and manure management actions have implications for soil quality.

[TOCB Report-3-5A *Croplands* **ETPW-242**] The effects on biodiversity of **ETPW-242** are likely to be similar to those of **ETPW-252** and **ECCM-003**, both of which have full assessments under reduced fertiliser use (Report-3-5A *Croplands*). There are likely to be some benefits to biodiversity of reducing fertiliser use, but much of the published evidence is from studies reducing fertiliser, pesticide and herbicide use (Dicks et al. 2013), so the effects and magnitude of potential biodiversity benefits from reducing fertiliser use are not well understood.

RAG rating for specific ecosystem biodiversity service (for **ETPW-242**):
AMBER L* maintaining species / wider biodiversity
AMBER TL* presence of rare and priority species

[TOCB Report 3-6 *Carbon* **ETPW-242**] According to Bai et al. (2019), reduced nitrogen fertiliser inputs will likely lead to greater SOC storage benefits brought about by “climate-smart agriculture” interventions including:

- Use minimum-tillage or no-tillage cultivation [**ETPW-092**]
- Use green manures within the rotation [**ECCM-023**]
- Minimise bare soil to reduce soil loss e.g. cover crops, crop residues, trees coppice etc. [**ECPW-002**].

[TOCB Report-3-5B *Grassland* **ECPW-171**] Positive benefits for biodiversity of grassland habitats and the species that are associated with them.

[TOCB Report-3-2 *GHG* **ECAR-015**] Benefits of reducing fertiliser use include the reduction of loss of N_2O into the atmosphere and reduced run-off, improving water quality. Trade-offs centre around the cost of establishing and maintaining clover / legumes in swards.

3.6.4.3 Magnitude

Local reductions will in theory cause local ammonia emission reductions. Fractional benefit proportionate to the decrease in fertiliser applications

3.6.4.4 Timescale

Lower fertiliser inputs will have instant effects

3.6.4.5 Spatial Issues

Context dependent.

3.6.4.6 Displacement

If productivity is reduced, to maintain the same economic output, more intensive fertiliser application may be needed in other locations

3.6.4.7 Maintenance and Longevity

If low inputs can be maintained, can last a few years.

3.6.4.8 Climate Adaptation or Mitigation

Limit on where to grow clover if changing climate. Temperature and climate changes could switch permanent grasslands from a sink to a source.

3.6.4.9 Climate Factors / Constraints

Limit on where to grow clover if changing climate.

3.6.4.10 Benefits and Trade-offs to Farmer/L-and manager

Lower yield if lower fertiliser input, very context dependent.

3.6.4.11 Uptake

Yield issue due to lower inputs needs to be addressed otherwise potentially low uptake.

3.6.4.12 Other Notes

3.6.5 ECCM-006: ECCM-077: ECCM-078: ECCM-079: AQ-04

ECCM-006: Replace urea and Urease Ammonium Nitrate (UAN) fertiliser with ammonia nitrate fertiliser for Nitrogen applications
ECCM-077: Use of urease inhibitors with urea fertilisers
ECCM-078: Use of polymer coated urea (slow release)
ECCM-079: Use nitrification inhibitors with nitrogen fertiliser manures, applied to grassland and animals (slow release bolus)
AQ-04: Use fertiliser with urease and nitrification inhibitors

There is a large industry researching approaches to more cleanly apply fertilisers to crops so that the nitrogen and other nutrient use efficiency is maximised and waste/loss to the environment is minimised. This group of actions consider different substitutions or modifications of currently used fertilisers.

3.6.5.1 Causality

Urea is the most used nitrogen fertiliser and is often applied as urea ammonium nitrate (UAN), which may be an ammonia emission source after application (Nikolajsen et al. 2020). Emission levels of UAN-derived

ammonia can vary between applications, with the highest ammonia emissions reported in late summer (17% of applied nitrogen). Plot experiments in the UK have shown that ammonia emissions from UAN fertiliser were higher than from ammonium nitrate or urea with urease inhibitor (Cowan et al. 2019), therefore replacement would be a logical action **(ECCM-006 GREEN; AQ-04 GREEN).** The purpose of using nitrification/urease inhibitors is to lower the degree of nitrogen leaching to ground and surface waters as well as ammonia and nitrogen oxide emissions to the atmosphere. They allow for the extension of nitrogen availability from 6 to 8 weeks to 8–16 weeks and, at the same time, reduce its losses Klimczyk et al. (2021)
It has been reported in a recent review that losses for urea and urea-ammonium nitrate solution (UAN) were higher than in the case of ammonium nitrate (3%). The analysis of the Department of Environment, Food and Rural Affairs (Defra) regarding the average nitrogen emissions for various fertilisers shows that compared to ammonium nitrate, UAN displays approximately 4 times higher ammonia emissions, while those of urea may even be up to 7 times higher. Based on data compiled within the European Monitoring and Evaluation Programme (EMEP), one may assume that there may be even a 6-fold increase in emissions for UAN and a 19-fold increase with the use of pure urea (Klimczyk et al. 2021). **(ECCM-077, ECCM-078 GREEN; ECCM-079 AMBER)**

The "4R" fertiliser strategies (right type, right rate, right timing, right placement) are recommended to improve nitrogen use efficiency and associated ammonia loss (Young et al. 2021). In a recent review and synthesis of a meta-analysis, it was reported that urease inhibitors and controlled-release (also slow release) fertilisers decreased ammonia emissions by − 74% to − 44% while nitrification inhibitors mostly increased ammonia, outcomes ranging from −5–21%. The results from their synthesis support previously published results that urease inhibitors and controlled-release fertilisers are more effective at reducing ammonia emissions by reducing soil ammonium concentrations, while nitrification inhibitors are more effective at reducing nitrous oxide emissions. An obvious choice to avoid pollution swapping would therefore be using fertiliser with both urease and nitrification inhibitors. In addition to chemical urease inhibitors, natural urease inhibitors (e.g. extracted from garlic or onions) should be considered as well and more research into those is needed (Matczuk and Siczek, 2020). Newer technologies to improve nitrogen use efficiency from fertilisers might include nanotechnology and more research and development could provide more options in the future (Dimpka et al. 2020).

3.6.5.2 Co-Benefits and Trade-offs

One trade-off is pollution swapping with nitrous oxide in the case of ammonium nitrate and urease inhibitors (Cowan et al. 2019). Co-benefits would be obtained by using urease and nitrification inhibitors simultaneously to reduce nitrous oxide and ammonia emissions at the same time (Young et al. 2020).
Concerns about inhibitor safety to human health have been raised when the nitrification inhibitor DCD appeared as a residue in milk (Ray et al. 2021). Natural alternatives to chemical urease inhibitors could a solution.

3.6.5.3 Magnitude

Depending on uptake, using urease and nitrification inhibitors together would significantly lower ammonia and nitrous oxide emissions on UK scale.

3.6.5.4 Timescale

Could be implemented relatively quickly.

3.6.5.5 Spatial Issues

Would be applied widely.

3.6.5.6 Displacement

None.

3.6.5.7 Maintenance and Longevity

Could be done long term.

3.6.5.8 Climate Adaptation or Mitigation

Mitigation potential from reducing nitrous oxide emissions.

3.6.5.9 Climate Factors / Constraints

Not applicable.

3.6.5.10 Benefits and Trade-offs to Farmer/L-and manager

Uncertainty surrounding yield/nitrogen use efficiency.

3.6.5.11 Uptake

If yield issues addressed, no barriers to uptake.

3.6.5.12 Other Notes

None

3.6.6 ECPW-106: ECPW-115: ETPW-255

ECPW-106: Target application of fertiliser (time, location, soil type, environment, weather at time of application and afterwards) to match crop need and minimise losses

ECPW-115: Switch to efficient / precision fertiliser application machinery (e.g. trailing hose, trailing shoe or injection, GPS)

ETPW-255: Use remote sensing techniques to monitor crop requirement and vary application of N

3.6.6.1 Causality

It has been reported in a recent review and synthesis of a meta-analysis that improving fertiliser timing and placement increased yield 4.0% and 5.0% and by association minimised losses Young et al. (2021). Ammonia emissions showed clear decreases due to organic fertiliser (−52%), right fertiliser placement (−43%), timing (−32%), and rate (−31%), as well as combined fertiliser (−28%). However, it is noted that the knowledge and ability to optimise all of these parameters can be challenging in the real world. **(ECPW-106 AMBER)**. Ammonia emissions can be managed via optimised precision fertiliser application methods: reducing ammonium levels in the product, dose and during the emission time after application reduce the chance that available ammonium is emitted as ammonia **(ECPW-115 GREEN)** For that reason, almost all agronomic fertiliser manuals recommend incorporation of manure and ammonia fertilisers into the soil (Young et al. 2021). It has been reported that remote sensing techniques such as red-edge-based reflectance index NRERI can be used to estimate nitrogen uptake by wheat and to monitor risk areas where N fertilisers might be overused with the caveat that any predictions might be weak (Holub et al. 2020). In theory, any technological tool resulting in reduced N input will by definition also reduce ammonia emission. However, limited data are available, making it difficult to generalise. The "4R" fertiliser strategies (right type, right rate, right timing, right placement) are recommended to improve nutrient (especially nitrogen) use efficiency and therefore minimise N loss including ammonia (Young et al. 2021) **(ETPW-255 AMBER)**

3.6.6.2 Co-Benefits and Trade-offs

Potential pollution swapping needs to be considered and any nutrient and manure management actions have implications for soil quality.

[TOCB Report-3-5A *Croplands* **ETPW-255**] If **ETPW-255** results in reduced fertiliser use, the effects on biodiversity are likely to be similar to those of **ETPW-252** and **ECCM-003**, both of which have full assessments under reduced fertiliser use (Report-3-5A *Croplands*). There are likely to be some benefits to biodiversity of reducing fertiliser use, but much of the published evidence is from studies reducing fertiliser, pesticide and herbicide use (Dicks et al. 2013), so the effects and magnitude of potential biodiversity benefits from reducing fertiliser use are not well understood.

RAG rating for specific ecosystem service (for **ETPW-255**)
AMBER L* maintaining species / wider biodiversity
AMBER TL* presence of rare and priority species

[TOCB Report-3-2 *GHG* **ECPW-115**] A range of co-benefits will emerge from the use of precision techniques. These include improved air quality, reduced run-off, improved water quality, better soil nutrient content, reduced wastage. There are also a range of trade-offs which need to be considered. These include the cost of the precision equipment (which is almost always greater than less precise equipment), the need for raised skill levels (and hence training) to effectively utilise the equipment and the raised management time which can be associated with the use of precision equipment.

In addition, the equipment will function best when geolocated, requiring additional investment in soil sampling and control of nutrient application.

3.6.6.3 Magnitude

Uncertain at this stage.

3.6.6.4 Timescale

Could be implemented if technology available.

3.6.6.5 Spatial Issues

On smaller plots remote sensing or precision farming might not be possible.

3.6.6.6 Displacement

Not applicable.

3.6.6.7 Maintenance and Longevity

Uncertainties still too high.

3.6.6.8 Climate Adaptation or Mitigation

Technologies might have to be adapted for changing conditions.

3.6.6.9 Climate Factors / Constraints

Technologies might have to be adapted for changing conditions.

3.6.6.10 Benefits and Trade-offs to Farmer/L-and manager

Not known.

3.6.6.11 Uptake

Costs could be a limitation for smaller farmers.

3.6.6.12 Other Notes

None

3.6.7 ECPW-109: ETPW-248

ECPW-109: Maintain optimum soil pH
ETPW-248: Test soil regularly for pH and adjust management practices accordingly

3.6.7.1 Causality

It has been well documented that there is a relationship between soil pH and ammonia emissions as recently summarised in a synthesis of 113 meta-analyses (Young et al. 2021). However, maintaining 'optimum' pH is a vague action as it is not clear for what parameter it should be optimised, most likely for crop production which will be crop dependent and ammonia emission would be a secondary purpose. If optimised for reducing ammonia emissions, it would be useful but could have potential negative impacts on other parameters. **(ECPW-109 AMBER)** Testing the soil and adjusting the pH for minimising ammonia emissions would have limited benefits but would support farmer understanding of ammonia emission potential **(ETPW-248 Green, but very limited).**

3.6.7.2 Co-Benefits and Trade-offs

Possible trade-offs with greenhouse gases, especially nitrous oxide as emissions also pH dependent.

[TOCB Report-3-5B *Grassland* ETPW-248] Biodiversity benefits provided that the adjustments to management practices take account of the needs of the semi-natural habitats e.g. hay meadows and acid grasslands.

3.6.7.3 Magnitude

Uncertain but likely to be small and local, particularly given soil heterogeneity.

3.6.7.4 Timescale

Uncertain as changes in soil pH not simple, permanent or fast.

3.6.7.5 Spatial Issues

Generally, pH very spatially variable so even within one field benefits with high uncertainties.

3.6.7.6 Displacement

None.

3.6.7.7 Maintenance and Longevity

Uncertain as difficult to maintain the same pH.

3.6.7.8 Climate Adaptation or Mitigation

Potential pH changes due to climate change but high uncertainties/limited data.

3.6.7.9 Climate Factors / Constraints

Potential pH changes due to climate change but high uncertainties/limited data.

3.6.7.10 Benefits and Trade-offs to Farmer/L-and manager

Unknown.

3.6.7.11 Uptake

Unknown.

3.6.7.12 Other Notes

None

3.6.8 ECCM-011: Use Anaerobic Digestion of livestock wastes at central sites (with sustainability criteria to limit incorporation of purpose grown crops)

3.6.8.1 Causality

A recent meta-analysis of 89 peer-reviewed publications, quantified emission reduction potentials of abatement options for liquid manure management chains from cattle and pigs (Mohankumar Sajeev et al. 2018). Literature on the effects of anaerobic digestion on ammonia emissions revealed mixed results (Chantigny et al. 2007) with considerable variability. Estimates from the meta-analysis showed an increase in ammonia emissions by 13 ± 76% during the storage of digestate and a decrease of 8 ± 34% when applied to the soils. Overall estimates averaged over the storage and application stages indicate a tendency for a small decrease in ammonia emissions by 3 ± 45% for digestates relative to raw slurry (Mohankumar Sajeev et al. 2018). However, there is no available data on whether a central site would improve the benefits. (**ECCM-011 AMBER**)

3.6.8.2 Co-Benefits and Trade-offs

Analyses of emission reductions highlight the importance of accounting for interactions between emissions. In the meta-analysis only three out of the eight abatement options (frequent removal of manure, anaerobic digesters, and manure acidification) considered reduced ammonia (3–60%), nitrous oxide (21–55%), and methane (29–74%) emissions simultaneously, whereas in all other cases, trade-offs were identified (Mohankumar Sajeev et al., 2018). The results demonstrate that a shift from single-stage emission abatement options towards a whole-chain perspective is vital in reducing overall emissions along the manure management chain.

3.6.8.3 Magnitude

Highly uncertain, though likely small given results of <5% difference relative to raw slurry (Mohankumar Sajeev et al. 2018).

3.6.8.4 Timescale

Medium-long, central facilities would need planning and developing.

3.6.8.5 Spatial Issues

Too uncertain.

3.6.8.6 Displacement

Yes, if waste moved from individual farm to central place.

3.6.8.7 Maintenance and Longevity

Should be long-lived if effective however a central facility would require on-going infrastructure maintenance

3.6.8.8 Climate Adaptation or Mitigation

Not applicable.

3.6.8.9 Climate Factors / Constraints

Not applicable.

3.6.8.10 Benefits and Trade-offs to Farmer/L-and manager

If central site, energy can't be used at individual farms directly.

3.6.8.11 Uptake

Unknown.

3.6.8.12 Other Notes

There is a need for comprehensive emission measurements to assess co-benefits and trade-offs.

3.6.9 ETPW-246: ECPW-292

ETPW-246: Switch to liquid application of fertiliser
ECPW-292: Supplement to shift from solid to liquid fertiliser application equipment

Note slurry liquid fertiliser actions are considered elsewhere in this report.

3.6.9.1 Causality

Lower ammonia emissions occur when urea ammonium nitrate solution is applied, because the urea contributes to about half of the total fertiliser content Klimczyk et al. (2021). The liquid form allows for the even distribution of the fertiliser by means of spraying or sprinkling, it accelerates the absorption of nitrogen by plants and ensures the high efficiency of fertiliser use, hence minimising losses (Klimczyk et al., 2021). (**ETPW-246** **GREEN**) It is well known that injection of fertilisers directly into the soil significantly reduces ammonia emissions because it lowers the air velocity above the fertiliser compared with surface application, and because gaseous ammonia is bound to soil colloids and soil water (Nyord et al., 2008). However, while it is known that the depths of injection of the liquid fertiliser is important there are large uncertainties and a lack of data associated with whether switching from solid to liquid application equipment will make a difference.

The key problem in the production of modified liquid fertilisers is the stability of the new mixture and the selection of compatible solvents with both the active substance and the dedicated liquid fertiliser. Due to a number of factors affecting nitrogen losses from fertiliser, it is difficult to predict an appropriate level in a given application Klimczyk et al. (2021). Future investigations should focus on developing new formulations of liquid fertilisers based on UAN with the addition of urease or nitrification inhibitors and equipment with which to make and apply. Supplementing equipment to enable this application would in theory reduce ammonia emissions **(ECPW-292 AMBER).**

3.6.9.2 Co-Benefits and Trade-offs

The improvement of nitrogen availability to crops and hence the increase in the economic efficiency of fertilisation may be achieved with the synchronisation of mineral nitrogen supply to the soil with the nutrient requirements of plants.

3.6.9.3 Magnitude

Too uncertain.

3.6.9.4 Timescale

Uncertain.

3.6.9.5 Spatial Issues

No anticipated issues.

3.6.9.6 Displacement

Not applicable.

3.6.9.7 Maintenance and Longevity

Should be possible long-term.

3.6.9.8 Climate Adaptation or Mitigation

None anticipated.

3.6.9.9 Climate Factors / Constraints

None anticipated.

3.6.9.10 Benefits and Trade-offs to Farmer/L-and manager

Could result in reduction of N applied needed, hence cost-saving.

3.6.9.11 Uptake

Wide uptake possible if equipment affordable.

3.6.9.12 Other Notes

n/a

3.6.10 ECAR-036: Avoid spreading of organic manures close to protected area sensitive to ammonia/sensitive habitats

3.6.10.1 Causality

No assessment.

3.6.10.2 Co-Benefits and Trade-offs

No assessment.

3.6.10.3 Magnitude

Too uncertain.

3.6.10.4 Timescale

Uncertain.

3.6.10.5 Spatial Issues

No anticipated issues.

3.6.10.6 Displacement

Not applicable.

3.6.10.7 Maintenance and Longevity

Should be possible long-term.

3.6.10.8 Climate Adaptation or Mitigation

None anticipated.

3.6.10.9 Climate Factors / Constraints

None anticipated.

3.6.10.10 Benefits and Trade-offs to Farmer/L-and manager

Could result in reduction of N applied needed, hence cost-saving.

3.6.10.11 Uptake

Wide uptake possible if equipment affordable.

3.6.10.12 Other Notes

n/a

3.7 Bundle: Systems action/Landscape actions

3.7.1 ECCA-035 Prepare and implement wildfire management plans

Ammonia emissions from wildfires and controlled burning are proportional to the area burned and the fuel loading in that area. In preparing and implementing wildfire management plans, the aim is to reduce the risk of uncontrolled burns, and some wildfire management plans will include controlled burns. David et al. (2021) reviewed US data and found that wildfires drive some exceptional air pollution events and that this may be predicted to increase with future climate change scenarios.

3.7.1.1 Causality

Ammonia and $PM_{2.5}$ are primary emissions from wildfires as is NOx as an additional precursor for $PM_{2.5}$, therefore any successfully prepared and implemented wildfire management plan would reduce ammonia and NOx emissions and $PM_{2.5}$. However, it is noted that air pollution reduction is generally not the primary purpose of wildfire management plans – it is the protection of human life, anthropogenic infrastructure and ecosystems (Thompson et al. 2011). However, with increasing awareness of the human health effects of $PM_{2.5}$ more detailed modelling and planning, including assimilation of wildfire information from wildfire dispersion estimates and satellite data, planning to minimise air pollution from wildfires is becoming integrated into planning (Li et al. 2020) and an awareness of the impact (Graham et al. 2020). **(ECCA-035 GREEN).**

3.7.1.2 Co-Benefits and Trade-offs

No assessment.

3.7.1.3 Magnitude

Limited to events rather than systemic reduction in ammonia, $PM_{2.5}$ and other air pollutants

3.7.1.4 Timescale

Implementing wildfire management plans would be an on-going activity.

3.7.1.5 Spatial Issues

The unpredictability of the location and extent of wildfires means all areas would need to consider emissions impact in the plans. Simple air quality modelling could be useful in timing of fires linked to weather conditions to minimise impacts on population centres.

3.7.1.6 Displacement

Not applicable.

3.7.1.7 Maintenance and Longevity

Ongoing.

3.7.1.8 Climate Adaptation or Mitigation

It is likely that higher frequencies of wildfire would be predicted without active planning and management. Therefore, active mitigation with this action is important

3.7.1.9 Climate Factors / Constraints

No assessment.

3.7.1.10 Benefits and Trade-offs to Farmer/L-and manager

Benefit to land managers is understanding risk and management of that risk or creating ammonia and $PM_{2.5}$ emissions.

3.7.1.11 Uptake

No assessment.

3.7.1.12 Other notes

None

4 KEY ACTION GAPS

Additional actions **AQ-01**, **AQ-02**, **AQ-03** and **AQ-04** have been included in this report summarised in the Table below.

				Reduced emissions of NH3	Reduced PM2.5	Air pollutants removed
AQ-01	free range poultry/pigs in woodland	Livestock management	Livestock management /Feeding and watering strategies	**LT****	**LT****	**LT****
AQ-02	Monitor AQ and GHG footprint of agricultural buildings to actively manage emissions	Livestock management	Livestock management /Housing & Handling	**L****	**L****	**N**
AQ-03	monitor indoor concentrations of ammonia and GHG	Livestock management	Livestock management /Housing & Handling	**L****	**L****	**N**
AQ-04	Use fertiliser with urease and nitrification inhibitors	Soil management and protection	Soil management and protection /Fertiliser, nutrient, manure and mulch management	**	**	**N**

5 EVIDENCE GAPS

There is a significant measurement evidence gap for many of the actions, particularly where many types of systems are implemented across the agricultural sector. An absence of assessment standards for ammonia emission reduction and core parameters to be measured for assessments means that quantitative evidence for many actions is missing.

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