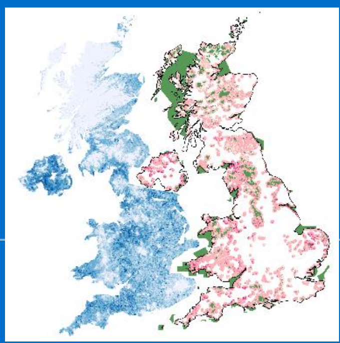
UK Centre for Ecology & Hydrology

Ammonia Reduction by Trees (ART)






Summary Report

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UKCEH contact details Bill Bealey
UKCEH, Bush Estate, Penicuik, Midlothian, EH26 0QB

e: bib@ceh.ac.uk

Authors Tang Y.S., Braban C.F., Dick. J.D., Vanguelova E., Timmis R., Pentecost, A., Fisher B., Carnell, E., Martin Hernandez C., Arkle P., Brass, D., Gill, R., Davies R., Stephens A., Iwanicka A., Mullinger N.J., Cowan N., Simmons I., Jones R., Shutt M., Whyatt D., Benham S., Broadmeadow S., Mansfield P., and Bealey W.J.

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We thank all the Cumbrian farmers that hosted the ammonia monitoring work on their farms.

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Executive Summary

Ammonia is emitted from the manures and slurries of livestock production in housing, storage and spreading practices. This loss of nitrogen from the farming system leads to a multitude of environmental issues. The fertilising effect nitrogen deposition to semi-natural habitats from the atmosphere causes changes in species composition and a decline in species richness. By mitigating ammonia in the landscape these effects can be avoided or reversed. Technical and management measures to improve emissions from housing, storage and spreading are seen as the first line of defence to reduce ammonia emissions but trees capture pollutants, and planting treebelts around hot-spots of ammonia in the landscape can mop up ammonia and reduce impacts to nearby protected sites.

The aim of Ammonia Reduction by Trees (ART) project was to provide new scientific evidence on tree planting for reducing the impact of ammonia emissions from farming to inform better advice, guidance and incentives for farmers on ammonia mitigation through treebelt planting.

The project consisted of three work packages (WP):

- WP1: Targeting planting of treebelts to protect sensitive habitats in the UK by collating and analysing emission and wind statistical datasets;
- WP2: Fieldwork to measure and test the effect of treebelts on ammonia concentrations across a treebelt at 5 case study farms;
- WP3: Farmer surveys to provide feedback on the practicalities and limitations of tree planting on farm.

The key findings from each work package are summarised below:

WP1: Targeting, key findings:

1. Prevailing wind direction and emission strength are the two key criteria for targeting areas suitable for tree planting for reducing the impact of ammonia emissions;
2. Combined scoring of emissions and wind direction provide a suitable method for targeting planting to address ammonia sources near (within 5Km) of sensitive protected sites;
3. Planting treebelts at any emission source should use the prevailing wind statistics to plant a treebelt on the downwind side of a source.

WP2: Fieldwork and modelling, key findings:

1. It can be shown that trees have an effect on the ammonia (NH_3) plume emitted from livestock housing and that there are interactions with the treebelt through deposition and dispersion effects.
2. This demonstrates treebelts have the potential for NH_3 mitigation, and that strategically planted treebelts in the landscape can mitigate NH_3 concentrations locally (~20% see bullet below) to protect sensitive semi-natural sites downwind of livestock housing, plus take some NH_3 emitted out of the atmosphere though re-capture.
3. At one farm (Poultry 2), an open gap in the tree belt was used to investigate the difference a treebelt would make on the NH_3 concentration. A significantly larger reduction in NH_3 (-59%, $p = 0.02$) was observed at the monitoring point behind the treebelt, compared to the open transect (-40%), which is likely to be due to increase dispersion and canopy capture. The results confirm previous studies that treebelts cause NH_3 concentrations to decline more rapidly with distance from the poultry housing compared with open land.
4. This in conjunction with other benefits of tree planting mean that ammonia recapture by trees is part of the toolkit of solutions for reducing N pollution.

5. A high-resolution monitoring approach with NH_3 and carbon dioxide (CO_2) tracer has significant potential to be used with meteorology to understand in detail the impact of sources on farming landscapes and integrate carbon and nitrogen footprints.
6. At another farm site (Dairy 2), with a mature woodland downwind of the dairy farm, smaller NH_3 concentrations in the centre and on the other side of the woodland, compared with the background site suggested that the established woodland captures NH_3 from the dairy farm and grazing emissions from the surrounding fields.
7. Changes in ammonia concentrations across the treebelt at farm Poultry 3 using three different methods (ALPHA®, AiRRmonia and DPAS (directional passive ammonia sampler) were comparable (a range of 41 - 45%) when averaged over the four sampling periods. This showed good correlation in the measurement techniques.
8. DPAS measurements before and after the tree shelter belts, normalised for a 25m tree depth, indicate that the percentage reduction in ammonia by trees ranged from 20% in well-mixed background air to 60% for ammonia from the ranging area.
9. Findings from ecological monitoring suggest that the trees have been growing faster nearer to the farm buildings where NH_3 concentrations were higher. Data also suggest that trees were accumulating higher concentration of nitrogen and have higher canopy nitrogen uptake in their canopies nearer the livestock sheds.
10. The results from this study demonstrate that fast growing tree species such as Poplar, Willow, Birch and Ash take up significantly higher (at least double) amounts of nitrogen in their leaf tissue, compared to slow growing tree species such as Rowan, Hazel and Sycamore.
11. Connected with growth, trees closer to ammonia sources had higher Leaf Area Index (LAI) and captured higher amounts of nitrogen in their leaves.
12. A survey at 2 farm treebelts of the presence/absence of target nitrogen-sensitive or nitrogen-tolerant lichen species on trees showed low diversity of lichen flora, and the species present indicated a high level of nitrogen deposition in both woodland areas and at the control field sites. NH_3 is slightly lower at the control sites but above critical levels for lower plants. NH_3 emissions from the two farms are affecting the lichen flora in the landscape with high background ammonia levels.
13. The presence of woodland appeared to have an ameliorating effect on the lichens perhaps resulting from a direct influence of the trees on deposition and dispersion of ammonia.
14. A strong diurnal cycle is observed in the NH_3 data from two ammonia analysers (LGR and AiRRmonia), and at sites before and after the treebelt. Smallest concentrations are in daytime and highest at night-time. This will be primarily due to diurnal changes in the boundary layer height, meteorological conditions and the farm management of the poultry emissions, with the hens inside the shed at night and ranging in the treebelt during the day.
15. Using CH_4 and CO_2 as conservative tracers for NH_3, the uptake of NH_3 by the trees was estimated to be between 0.3 – 6 % but this was with a high uncertainty due to the relatively small fraction of the wind data meeting required criteria (e.g. wind speed > 2 $m\ s^{-1}$, wind direction = 200 – 250 degrees i.e. downwind of source, all analyser operational; 1969 data points out of ~80000 in campaign).
16. Modelling with the SCAIL model (with no treebelts present) further validated the effect that treebelts have an effect on the NH_3 plume through canopy dispersion (increased turbulence and mixing) and deposition (capture and uptake by trees). For most of the farm treebelts, the change in the concentration measurements (2-weekly) before and after the treebelts were higher than in the modelled runs.
17. Using the Moddas-OpenFoam model to estimate canopy capture of ammonia, the mature woodland at Dairy 2 is estimated to reduce ammonia emissions by 80% and

tree belts planted for ranging poultry by 0.1% to 4.2%, with larger predicted reductions related to larger tree canopy depth and size.

18. Treebelts planted for ranging livestock are unlikely to capture significant amounts of NH_3 in the first 5 years based on modelled outputs at farm Poultry 4 (planted 5 years before the field campaign).

WP3: Farmer Surveys – key findings

19. Questions based on the Adoption and Diffusion Outcome Prediction Tool (ADOPT), was selected as this model explicitly addresses the motivation of farmers, relative advantages of a new innovation (such as planting trees to mitigate ammonia) and the learning associated with the new innovation.
20. Providing guidance and knowledge about ammonia and treebelts brought about a more positive reaction to planting treebelts for ammonia mitigation on their farm.
21. Using the ADOPT model farmer attitudes to the practice of planting trees for ammonia mitigation increased in the second set of farmer 1:1 interviews after knowledge and guidance had been shared. Peak adoption levels (farmers who would adopt the practice) increased from 45% to 85% after this knowledge was given. The time to adopt the practice also decreased from 18 to 10 years.
22. A further larger on-line farmer survey was carried out based on the ADOPT questionnaire using the same 22 questions about planting trees for ammonia mitigation. From 148 respondents the results gave similar (often the same) ADOPT scores across the questions as with the five in-depth farmer interviews. However, some questions scored much lower represented by a higher perception of risk, lower knowledge, and lower profit advantage. As a consequence, the peak adoption peak was only 2% with a longer time to adopt the practice of 15 -19 years.
23. Additional survey questions were asked on the benefits of planting trees on the farm and motivation behind that. Over half of all farmers said that they would consider planting shelter belts for other benefits than ammonia mitigation, and only ~10% of farmers clearly stated that they would not consider planting tree shelter belts. Of the expected benefits from planting tree the majority (54%) suggested that environmental benefits were the main advantage.
24. When asked about their motivation behind future planting of trees it was clear that the main motivation would be through financial support of grants and incentives with 60% of farmers stating this.

Recommendations for policy and future work

1. The research focused on treebelts planted for free-range laying hens (apart from one mature woodland). These treebelts are quite well spaced with 2 metre planting between trees, but 4-5 metre between rows to allow for access for mechanical maintenance (E.g. mowing /topping). This planting system give rise to low LAI, as reflected in our measurements, and low ammonia capture rates. Further measurements should now be made downwind of livestock housing E.g. pig, poultry or dairy housing, with denser treebelts or woodland. This would give a better understanding of how new treebelts may perform to mitigate against emissions from housing alone. Finding suitable sites could be challenging.
2. Furthermore, work looking at the effect of specific species selection and changes in LAI would help support the ammonia/tree calculator. Some work being carried out in 2022/3 under the Defra Natural Capital and Ecosystem Assessment programme (NAEI) can support some of this work.
3. The farmer surveys showed a clear interest in learning and need for further guidance on developing the use of treebelts for ammonia mitigation and incorporating it into wider farm tree benefits. The guidance document on farmtreestoair website should be

updated to provide more planting schemes and a simpler checklist approach. Some work has gone into the ammonia/tree calculator which provides further guidance on prevailing wind direction at a farm location, and includes suitability for planting to mitigate the effects on protected sites.

4. For treebelt adoption levels to improve it needs to be done in a way which fits with other farm development plans and be made economic through grant or financial support.
5. Planting treebelts for ammonia mitigation are an additional measure to complement the more immediate emission reduction measures such as in housing, storage or spreading improvements, but can be seen as a holistic approach to providing a host of further benefits, including biodiversity and carbon capture. The long-term nature of the development of treebelts means that full benefits from the particular aspect of ammonia capture and protection of downwind sites means a careful plan to implement in environmental land management schemes or other schemes needs to be done.
6. It is recommended that the 5 farm study sites should be revisited in 5 years time following further growth of the treebelts and development of the farm's C and N emission budgets to begin to build a long-term evidence base.
7. Meteorological standards and use of measurements and their interpretation with models needs significant further work, but ART has provided the first steps.
8. Low cost approaches to measurement of NH_3 and greenhouse gases (GHGs) are in development but high quality measurement are imperative to be implemented long term to develop the necessary capabilities.

Background

Agricultural practices account for over 80% of ammonia (NH_3) emissions within the UK[1], with releases from livestock housing and manure management through storage and spreading. Locally, the deposition of nitrogen (N), emitted in the form of ammonia, can cause eutrophication and acidification effects on semi-natural ecosystems, leading to species composition changes and reduced biodiversity[2]. Species adapted to low nitrogen (N) availability are at a greater risk from this effect including many slow-growing lower plants, notably lichens and bryophytes.

The Clean Air Strategy 2019 has given significant focus on the impact of ammonia emissions and the subsequent atmospheric N load on ecosystems together with the particulate form of ammonia affecting human health outcomes. Furthermore, over 60% of the UK's semi-natural habitats exceed their critical load (threshold limit where damage is caused) for nitrogen. Mitigation measures have been proposed by Government to support farmers in providing reductions. The Code of Good Agricultural Practice (COGAP) for Reducing Ammonia Emissions guidance has been developed to support farmers with practical steps to reduce their ammonia emissions including mitigation options like planting treebelts to 'scavenge' ammonia.

Trees and other 'green infrastructure' have been researched over the years with a focus on the urban environment and human health impacts from pollutants such as nitrogen oxides (NOx) and particulates[3,4]. There is a combined effect (Figure 1) of treebelts on ammonia concentrations through:

i) capture of the plume by the canopy by deposition to the leaf surface and uptake through the stomata, and
ii) increased mixing and dilution of the plume though the creation of eddies and turbulence from the treebelt.

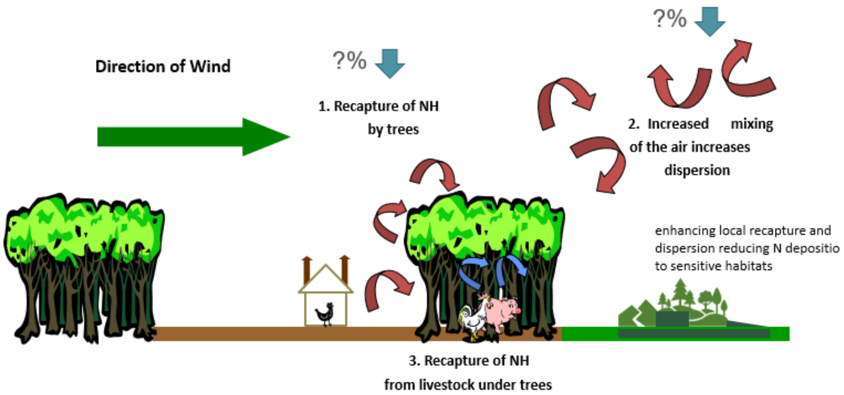

Figure 1: combined effect of treebelts on ammonia concentrations through i) capture of the plume by the canopy by deposition to the leaf surface and uptake through the stomata and ii) increased mixing and dilution of the plume though the creation of eddies and turbulence.

The fraction of ammonia recaptured varies depending on the source strength, meteorological and surface conditions. Studies by Fowler et al. (1998), showed that between 3% and 8% of NH_3 emissions from a livestock building were deposited in woodland within 300m of the source. Further work by Bealey et al. (2016), focussed on a range of planting strategies showed that woodlands designed to recapture NH_3 from a range of livestock sources (at around 10-20 metres) could recapture a substantially greater fraction of NH_3 emissions, up to 20%. In addition rough landscape features such as treebelts can

1 Misselbrook, T. H., Gilhespy, S. L., Cardian, L. M., Williams, J. and Dragosits, U. (2016) Inventory of Ammonia Emissions from UK Agriculture 2015, Inventory Submission Report, October 2016, DEFRA contract SCF0102.

2 Bobbink, R., M. Hornung, and J. G. M. Roelofs (1998). The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation, J. Ecol., 86, 717-738.

3 Janhäll, S. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. Atmospheric Environment, Volume 105, Pages 130-137,

4 Nowak, D.J., Crane, D.E., Stevens, J.C. Air pollution removal by urban trees and shrubs in the United States, Urban Forestry & Urban Greening, Volume 4, Issues 3–4, 2006, Pages 115-123,

also help disperse ammonia, reducing concentrations near sources and therefore decreasing the most extreme impacts on nearby sensitive receptor ecosystems.

The aim of the Ammonia Reduction by Trees project was to provide new scientific evidence on tree planting for reducing the impact of ammonia emissions from farming in order to inform better advice and support to farmers on ammonia mitigation and guidance. The work was organised into three work packages which were:

- WP1: collate and analyse emission and wind statistical datasets to provide a targeted approach to planting treebelts to protect sensitive habitats in the UK;
- WP2: to measure and test the effectiveness of treebelts in mitigating ammonia concentrations across a treebelt at 5 case study farms;
- WP3: to gather information and undertake farmer surveys to provide feedback on the practicalities and limitations of tree planting to mitigate ammonia emissions.

1 WP1: Priority Targeting of treebelts for ammonia mitigation in the landscape

[Authors: Cristina Martin Hernandez, Ed Carnell, and Bill Bealey]

1.1 Scope

This work package within the Ammonia Reduction by Trees project has collated and analysed the background datasets, and provided a targeted approach with combined indicators for planting treebelts based on datasets of:

- NH_3 emissions,
- prevailing wind direction, and
- distance from a protected site (SAC and SSSI).

A spatial dataset was produced to score suitable areas for planting treebelts to reduce impacts of ammonia on the UK's protected site network.

1.2 Approach

Three key datasets were used for building the targeting;

i) wind data (2 x 2 km grid resolution) from the UK Met Office operational NWP (Numerical Weather Prediction) Unified Model (UM) - this dataset was used to extract hourly data wind statistics for the UK of wind speed and wind direction. Years 2016-2020.

ii) SAC/SSSI site boundary GIS data.

iii) high resolution (1 x 1 km grid resolution) UK agricultural ammonia emission maps (Figure 2) were used to identify likely emission hotspots surrounding SAC/SSSI site boundaries. NH_3 disperses and dilutes rapidly downwind of sources and therefore emission sources >5 km from SACs and SSSIs were not considered to be suitable for tree planting for this purpose. Although emissions are likely to vary substantially at a sub-grid resolution, for this national analysis we assume that each 1 x 1 km grid estimate is representative of the sources within each cell and associated suitability for tree planting.

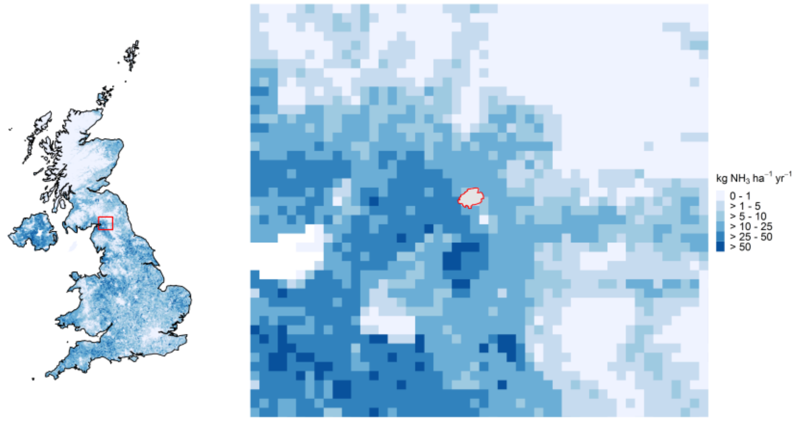

Figure 2: 2018 UK agricultural NH_3 emissions and zoomed in to study region

The probability of an emission source (represented by a 1 x 1 km grid-square) being upwind of a designated site was estimated by calculating the wind direction each grid-square to the nearest point of each designated site. This relationship was then compared to hourly wind data to determine how often an emission source is upwind of a designated site.

NH_3 emissions and relative wind direction were then categorised into scores of 1 – 5, and a combined score calculated (assuming equal weighting). For each 1 x 1 km grid cell, a score was assigned based on estimated agricultural emission estimate and also based on the location of each cell relative to wind direction. These criteria used to assign scores is shown in Table 1.

Table 1: Combined Indicator scores based on emissions and relative location of source and wind statistics.

Score	Agricultural NH_3 emission criteria (kg NH_3 ha^{-1} $year^{-1}$)	Relative location of source criteria (% of time upwind/within 45 degrees of wind)
1	≤ 5	≤ 20
2	> 5 – 10	> 20 – 40
3	> 10 – 25	> 40 – 60
4	> 25 – 50	> 60 – 80
5	> 50	> 80

1.3 Results

Wind statistics for the UK were averaged using the 2016-2020 meteorological dataset. Figure 3 shows the predominant wind directions across the whole of the UK and Cumbria area (red square) which includes, as an example, Bolton Fell Moss SAC (shown with red outline). It can be seen that the prevailing wind is predominantly from the south west but there are local variations, as would be expected in an area with significant amounts of complex terrain.

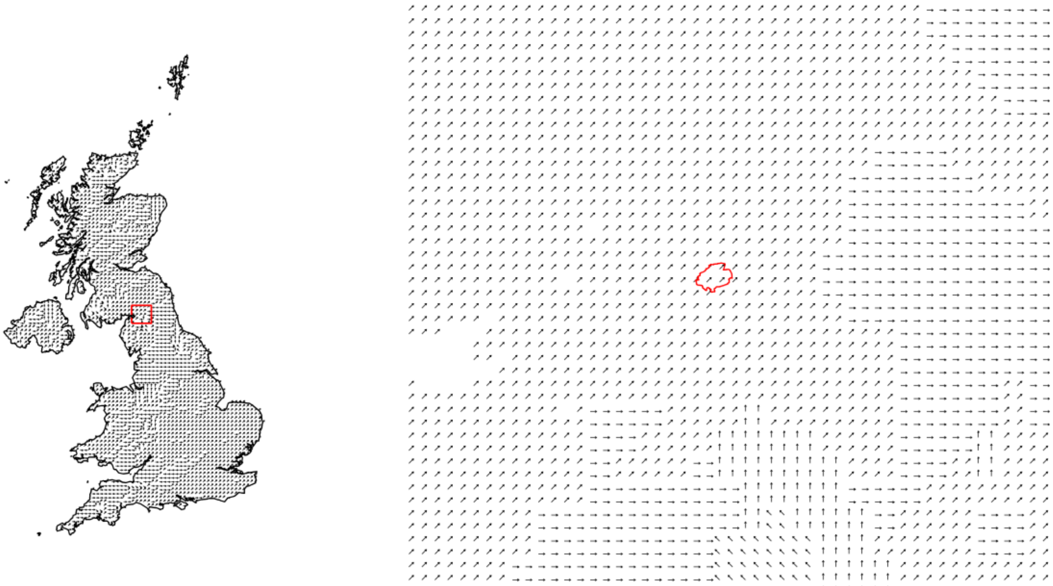

Figure 3: Prevailing wind direction across the UK and inset of study area. Data is available for every 2 x 2 km grid but is shown for the UK on a 10 km grid and at 2 x 2 km for the Bolton Fell Moss study area (in red right hand image).

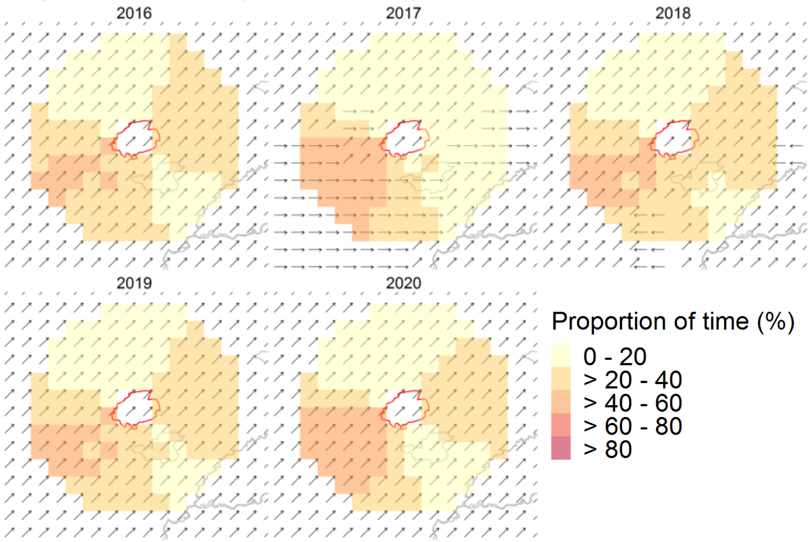

Figure 4: Annual proportion of time, using meteorological years 2016 to 2020, that potential emission sources are upwind (with 45 degrees of the prevailing wind) of Bolton Fens Moss SAC.

The number of hours an emission source site was upwind (within 45 degrees) was summarised on an annual basis and is illustrated for Bolton Fells Moss SAC (red outline) in Figure 4. The wind arrows around Bolton Fell Moss and the coloured areas show the percentage of time over the year the protected site is upwind of a grid square. The darker squares indicate the best areas to plant treebelts.

When more sites are included in the routine, Figure 5, the situation becomes quite complex as nearby sites have overlapping influences but the rule still applies.

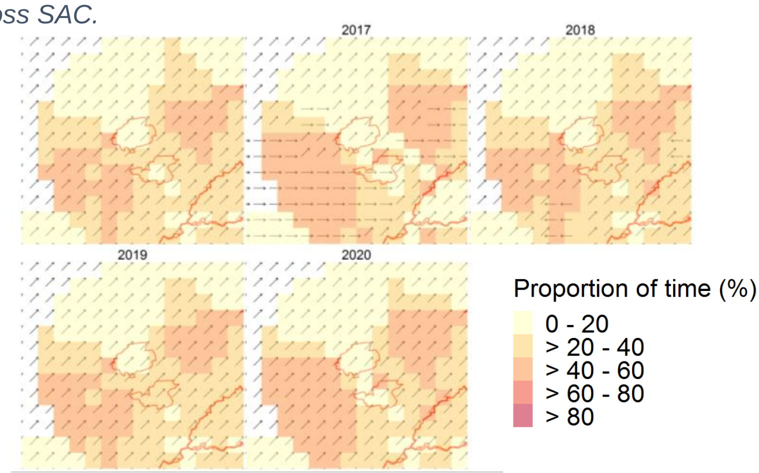

Figure 5: Annual proportion of time that potential emission sources are upwind (with 45 degrees of the prevailing wind) of all SACs surrounding

When scores of emissions and wind direction are combined in Figure 6 the influence of emission strength is evident as areas to the south score highly. The higher the score (darker the colour) the more suitable to plant trees. Figure 7 includes all protected sites and clearly shows a matrix of areas that are suitable for targeted tree planting. Figure 8 shows the map for the whole of the UK.

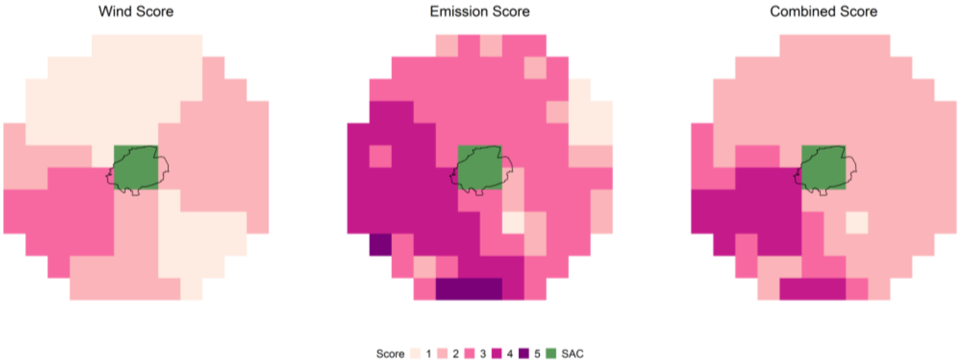

Figure 6: Upwind source scoring for Bolton Fells Moss SAC; LHS: Wind score associated with time that potential emission sources are upwind (within 45 degrees of the prevailing wind); Middle: annual emission estimates score; and RHS combined score. The higher the score (darker the colour) the more suitable to plant trees Green area indicates the protected site.

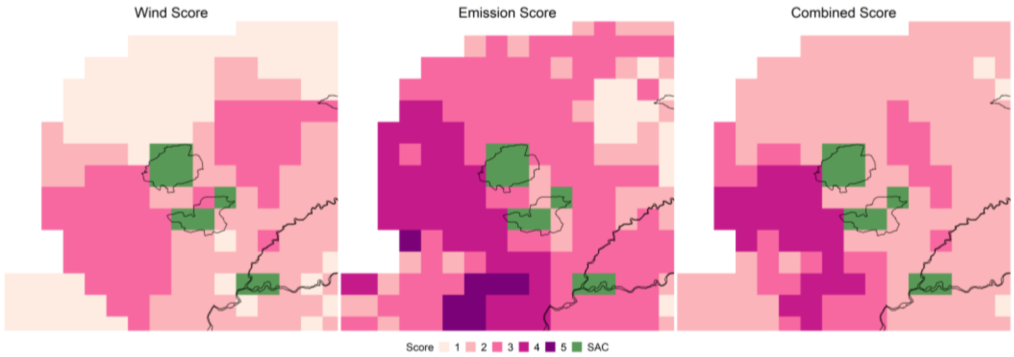

Figure 7: Upwind source scoring for SAC sites surrounding Bolton Fells Moss SAC; LHS: Scores 1-5 associated with time that potential emission sources are upwind (within 45 degrees of the prevailing wind) of all; Middle: annual emission estimates and RHS: combined score. The higher the score (darker the colour) the more suitable to plant trees, green area indicates the protected site.

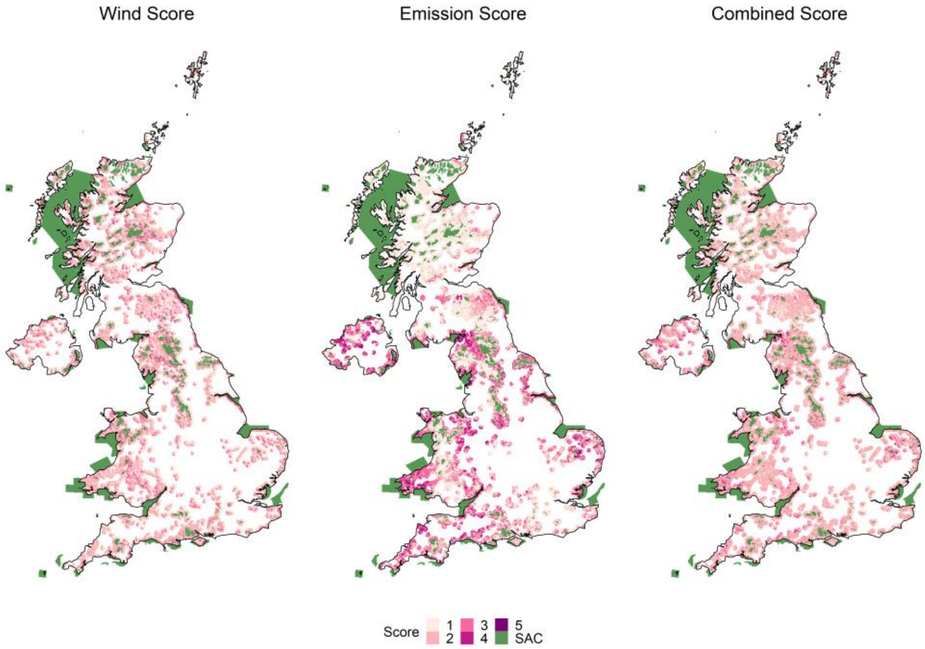

Figure 8: Combined scores (far right) for all SACs (green) across the UK based on Wind and Emissions scoring (1-5). The higher (darker the colour) the score the more suitable to plant trees. Similar data is available for SSSIs

1.4 Conclusions

- NH_3 emission strength is a key driver for assessing where tree planting options should be targeted to prevent nitrogen impacts on sensitive habitats on both the national and landscape scales. However, prevailing wind direction is another critical factor as tree planting should be carried out downwind of emission sources for ammonia capture and dispersion.
- Distance to the nearest protected site was considered as a suitable criterion as ammonia emissions will deposit onto nearby sites. However, sources with high emissions can have a similar effect on a site at greater distances so a balance of distance and strength were assessed and hence the 5 km buffer zone around sites was set.
- Single site assessment provides a quick way to define target areas for that site only while multi-site assessment in the landscape can start to pinpoint the optimal areas for tree planting.
- Combined scoring of emissions and wind direction provide a suitable method for targeting sources around protected sites.
- Planting treebelts at any emission source > 5 km from a site (or at an emission source that has a low combined score within a 5 km zone) should use the prevailing wind statistics to plant on the most frequent downwind side of a source.
- For a national policy agenda of reducing emissions planting downwind of livestock housing would have a positive effect as the tree canopy can recapture some of the ammonia plume.
- Alternatively, planting treebelts downwind of a source to reduce concentrations and deposition at protected sites is also a beneficial strategy for reducing critical load and level exceedance.

References

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2 WP2: Field case studies for monitoring ammonia reduction from treebelts

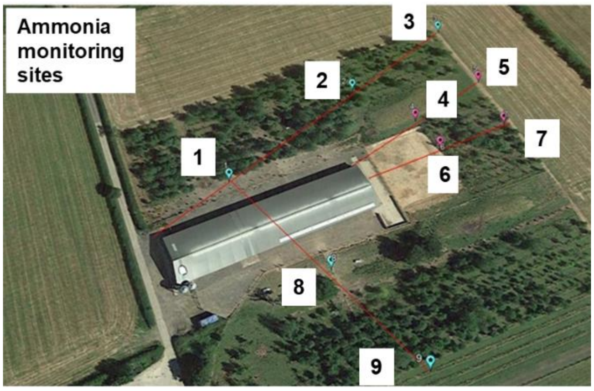
[Authors; Sim Tang, Christine Braban, Roger Timmis, Elena Vanguelova, Ben Fisher, Allan Pentecost and Bill Bealey]

2.1 Scope

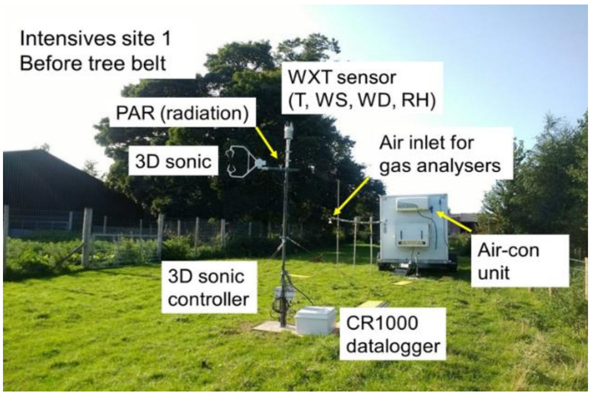
Monitoring sites at the five study farms with treebelts were established in early August 2020. Field and modelling studies were carried out to assess the fate of ammonia being emitted from livestock housing and the effect of treebelts downwind of the source. Experiments at each farm were designed to:

- Measure the spatial pattern of NH_3 concentrations along transects away from livestock buildings and the effect of nearby treebelts on the plume.
- To test the NH_3 concentration differences between open (no tree) transects and where there were trees, including one or two sites equidistant with open and tree transects.
- Carry out ecological measurements of trees along the transects to compare the proxy evidence of the ammonia concentration measurements provided. This included measurements of leaf area index (LAI), tree height, tree diameter, nitrogen content in leaves, and a lichen survey.
- Carry out at one farm intensive measurements for ammonia using different techniques together with on-site meteorological measurements.
- Run an air dispersion model to predict concentrations of ammonia without trees to compare with the measurements to determine if any difference observed might be caused by uptake or dispersion by the treebelts.

2.2 Approach



Five case study poultry and dairy farms were selected from a list of candidate farms identified in Cumbria. These have different age and depth of planted treebelts or existing mature woodland, and have contrasting size and orientation of livestock housing or slurry stores to the prevailing wind. Four of our farm treebelts are planted for free ranging laying hens. The treebelts are quite well spaced with 2 metre planting between trees, but 4-5 metre between rows to allow for access for mechanical maintenance (mowing /topping). This planting system is established to avoid egg laying outdoors.



The prevailing wind in the UK is mostly from the south-west. Ten monitoring sample points were established at each farm to provide measurements of atmospheric NH_3 concentrations over 7 fortnightly sample periods, in addition to on-site meteorology. The NH_3 concentration at each point in front of, in and behind the treebelt/woodland were compared and contrasted with modelling. Two intensive measurement sites were established at Poultry 3 farm, positioned on either side of a treebelt (23 m wide) downwind of a single poultry shed and ranging area. Measurements using continuous analysers were run for a period of 8 weeks and included three directional passive ammonia samplers (DPAS) to trial its performance in providing directional signal of NH_3.

2.3 Results

2.3.1 Dairy 2

Figure 9: Dairy sheds

Dairy 2 is a large dairy farm with a collection of housing and a slurry store on the south end of the farm buildings. An established replanted mature woodland (mixed broadleaf and conifer) is located to the east and north-east, approx. 70 m from the farm buildings, with a sensitive habitat (River Eden SAC) behind the woodland. The woodland is about 250 m deep, with some open areas. There are 350 dairy cows, including followers, which are housed year-round. Cattle grazed in the fields around the farm and in the fields behind the woodland.

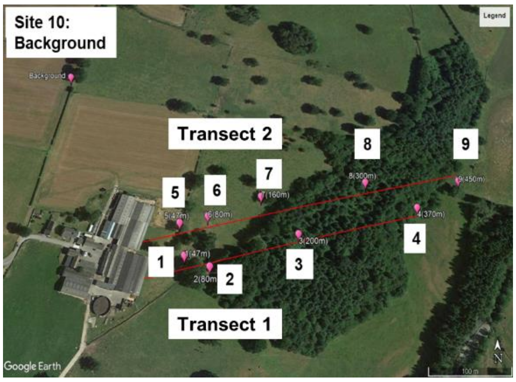


Figure 10: Transects (2) at Dairy 2 farm and monitoring points

Two parallel transects (Figure 10) were established and bimonthly measurements of ammonia were made together with tree and lichen surveys.

Ammonia Measurements (ALPHA)

In both transects, NH_3 concentrations declined with distance downwind of the farm, reaching similarly small levels of concentrations at site 3 (200 m NE of farm, mean = 2.8 µg NH_3 m^{-3}) and site 8 (300 m NE of farm, mean = 1.8 µg NH_3 m^{-3}). Both sites are in clearings in the centre of the mature woodland (Figure 11). NH_3 concentrations were smallest at sampling sites 3 and 8 within the woodland and at site 4 (mean = 2.2 µg NH_3 m^{-3}) at the end of the wooded transect (sites 1 – 4). The slightly larger concentrations at site 9 (mean = 2.8 µg NH_3 m^{-3}) compared with site 8 (mean = 1.7 µg NH_3 m^{-3}) may be due to site 9 being positioned within a fenced off hedge-line between 2 fields with cattle grazing.

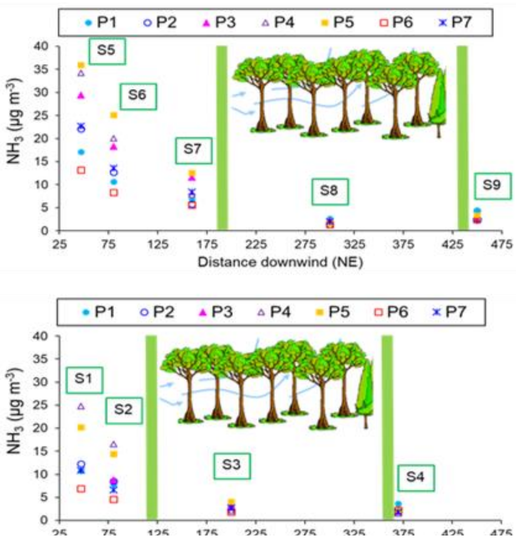


Figure 11: Changes in NH3 concentrations between an open transect (sites 5 - 9) and a wooded transect (sites 1 - 4) at Dairy 2 dairy farm, showing data from individual periods

Figure 12 compares the NH_3 concentrations (and % relative change) between paired open and wooded sites in the parallel transects. The comparisons showed larger reductions at Site 3 in the woodland (mean = -68 %) than the paired Site 7 in the open, and lends support to a reduction in NH_3 concentrations by trees.

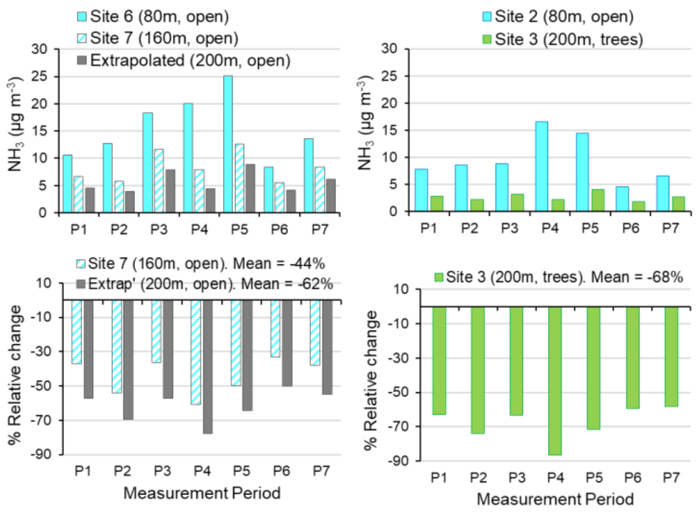


Figure 12: (TOP) Comparison of NH3 concentrations between paired sites (open and wooded) in the two parallel transects. Top left: Sites 6 (80m, open), 7 (160m, open, and extrapolated concentrations at 200m, open) and Top right: Sites 2 (80m, open), 3 (200m, trees). (BOTTOM) relative change in NH3 concentrations, showing larger reduction in concentrations (mean = -68 %) at site 3 in centre of woodland, compared with the paired site 7 in the open at a comparable distance along the parallel transect

Modelling

Analysis of the SCAIL modelling at this site examined the difference between two sets of sites along the transects – before and after trees. This was then compared with the measurements.

Table 2 shows some examples of this for 3 different bimonthly monitoring periods. A positive difference between model and measured (last column) indicates the change in concentrations are higher in the measurements indicating an enhanced 'dilution' effect on the ammonia plume by the treebelt.

Table 2: Modelled (SCAIL) vs measured (ALPHA) NH3 concentrations in µg m-3 for Dairy 2 farm for 3 sampling periods, and estimates of ammonia reduction due to the woodland (+ve difference SCAIL vs ALPHA indicates the measured change is higher (Green is woodland; SCAIL and ALPHA concentrations in µg NH3 m-3).

Period	Sampling Site	NH_3 SCAIL	ALPHA	SCAIL % conc △	ALPHA % conc △	SCAIL vs ALPHA
Period 3	1	13.73	5.25			
Period 3	2	6.23	8.88	56%	63%	**Difference**
Period 3	3	2.76	3.25			**8%**
Period 3	4	1.12	2.06			
Period 3	5	30.89	29.52			
Period 3	6	14.05	18.33			
Period 3	7	5.33	11.66	68%	81%	**Difference**
Period 3	8	1.73	2.26			**13%**
Period 3	9	0.88	2.44			
Period 3	10	2.32	6.21			
Period 4	1	24.05	24.78			
Period 4	2	11.37	16.52	69%	87%	**Difference**
Period 4	3	3.47	2.18			**17%**
Period 4	4	1.23	1.48			
Period 4	5	29.33	34.27			
Period 4	6	12.96	20.05			
Period 4	7	4.40	7.86	65%	84%	**Difference**
Period 4	8	1.54	1.28			**19%**
Period 4	9	0.86	2.42			
Period 4	10	1.92	5.77			
Period 5	1	29.21	20.17			
Period 5	2	14.42	14.47	68%	72%	**Difference**
Period 5	3	4.66	4.10			**4%**
Period 5	4	1.69	2.26			
Period 5	5	38.08	35.99			
Period 5	6	17.18	25.10			
Period 5	7	5.98	12.59	64%	87%	**Difference**
Period 5	8	2.14	1.60			**23%**
Period 5	9	1.21	3.39			
Period 5	10	1.14	2.99			

Figure 13 shows the wind roses for these periods showing the effect of changing concentrations from different dominant wind directions over each sampling period.

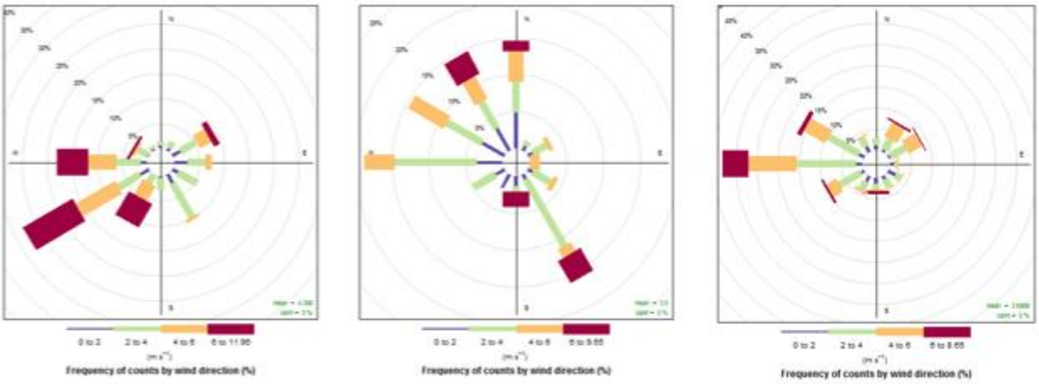


Figure 13: wind roses at Dairy 2 for sampling period 3, 4 and 5

Corticulous (bark) Lichen Survey

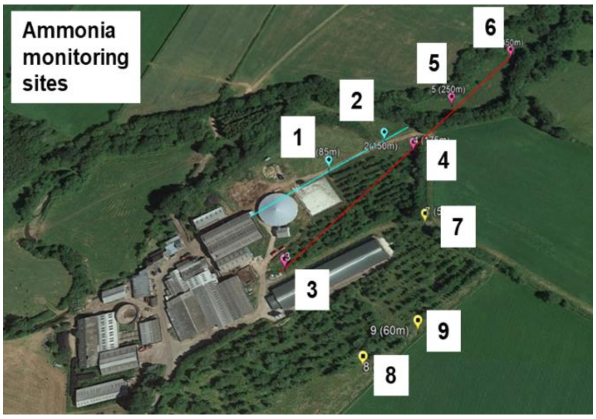


Figure 15: Dairy 1 with transects and sites.

Corticulous (bark) lichen surveys[5] were undertaken at Dairy 1 farm. This farm had a mix of dairy sheds, slurry stores and a poultry unit to the southeast. A planted treebelt and an ancient woodland (sites 5 & 6) were surveyed. The Nitrogen Air Quality Index (NAQI) values are plotted along the transects (sites 1-9) in Figure 14. The results show that the lichen flora of the trees is heavily impacted by atmospheric nitrogen sources and it is not possible to easily separate out the effects of local ammonia emission and the background sources of ammonia and NO_x. Sites 6 and 7, situated furthest from the farm, and sheltered to some extent by trees might have been expected to yield lower values but this was not the case, and the ‘control’ site 10 also recorded a high value. Site 1, near the slurry pit had the lowest value but the birch tree closest to this monitoring station was almost devoid of lichens, with only two of the branches out of five having any colonization, and that consisting solely of the N-tolerant species *Xanthoria parietina*. The resulting Lichen Indicator Score (LIS) was low, resulting in an anomalously low Nitrogen Air Quality Index (NAQI) score. In fact, the lack of colonization is more likely the result of a higher rather than a lower level of pollutant. This site is in a position likely to receive a considerable amount of locally produced ammonia emitted from farming activities.

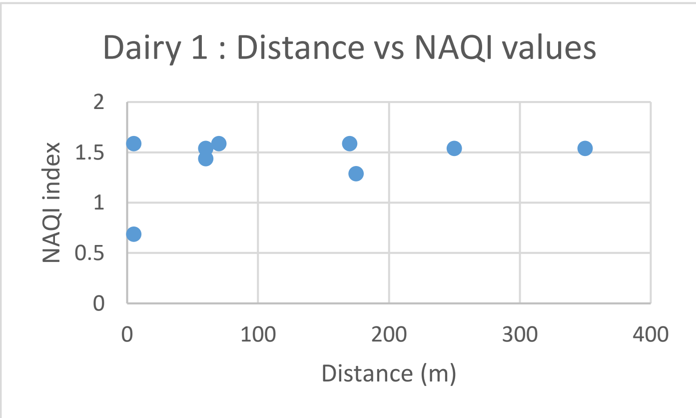


Figure 14: NAQI values along the Dairy 1 farm transects plotted against distance from nearest source.

[5] Monitoring air quality using lichens - field guide and app https://www.apis.ac.uk/nitrogen-lichen-field-manual

2.3.2 Poultry 2

Poultry 2 farm is a single poultry shed and treebelts planted on 3-sides of the shed (), which in theory is a simple case. The prevailing wind in the UK is mostly from the south-west with the treebelt situated to the north-east of the building. Planting is also < 35m from the housings, which would maximise the capacity of the treebelt for NH_3 capture. The farm has 2,000 birds in a single shed which has natural ventilation. A gap in the treebelt offered the opportunity to compare a wooded transect (sites 6, 7) with an open transect (sites 4, 5) (
Figure 16).

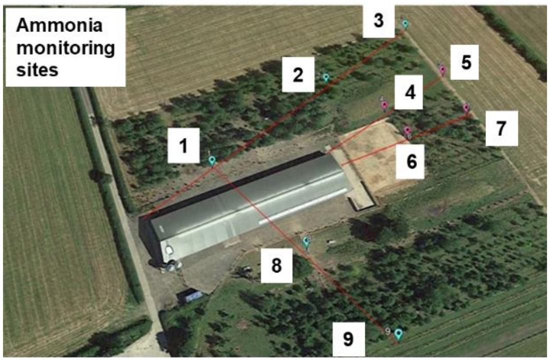
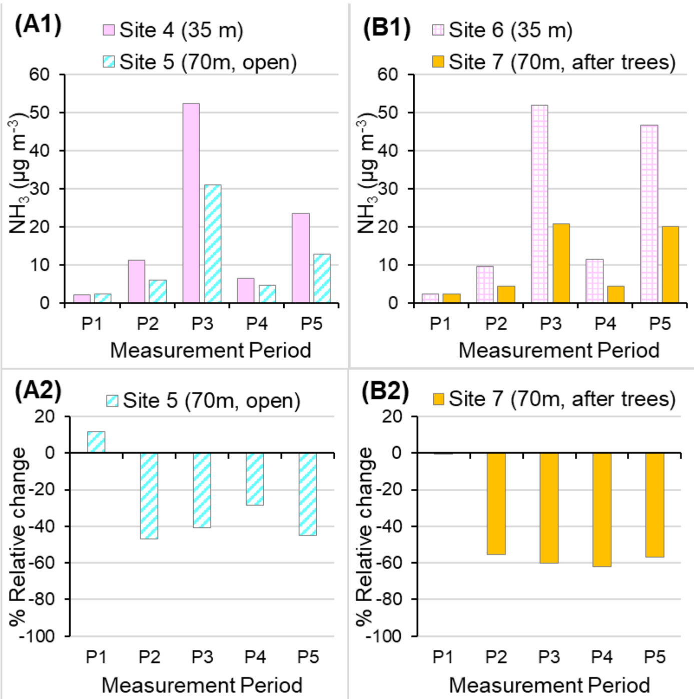


Figure 16 Poultry 2 farm showing locations of NH3 monitoring points for a detailed spatial assessment

Ammonia Measurements (ALPHA)

Site 5 is 35 m north-east of site 4, in a 10 m wide gap in the treebelt, whereas site 7 is located 35 m north-east of site 6, behind the 35 m treebelt. NH3 concentrations at site 5 (mean = 13.6 µg NH_3 m-3; periods 2 - 5) was larger than at site 7 (12.4 µg NH3 m-3). Since concentrations at each of the sites varied between periods, relative change in concentrations were calculated between paired sites for each of the periods (Figure 17).



Overall, a significantly larger reduction in NH_3 (mean = -59%, p = 0.02) was provided by site 7, compared with the paired site 5 located at the same distance in the open between the trees (mean = -40%). The results at Poultry 2 indicate that the treebelt captures NH_3 from free ranging hens and poultry sheds, as NH_3 concentrations declined more rapidly with distance from the poultry housing in wooded compared with open transect.

Figure 17: (TOP) Comparison of NH3 concentrations between sites in an open transect (A1) with other sites in wooded transect (B1). (BOTTOM) Relative change in concentrations, showing larger reduction in concentrations at sites located behind the tree treebelt (B2: mean = -50.8 %, n = 4)) than at site 5, with no trees (A2: mean = -40.3 %, n = 4), around a 10% difference.

Tree growth, leaf morphology and nutrient uptake

Tree sampling was carried out at all ammonia monitoring points, with additional points added for tree assessments to increase the number of points along the transects. Figure 18 shows that the tree height and diameter decline with distance away from the farm and tree height and diameter significantly declined between 10m and 30m, 70m and 90 m away from the farm. Tree diameters have much higher variability between species than tree height. Tree Leaf Area Index has also declined with a distance from farms. Tree canopy nitrogen uptake decreased with distance from Poultry 2 farm from on average 40 kg N/ha at 10 m to 17 kg N/ha at 90 m distance away from the farm.

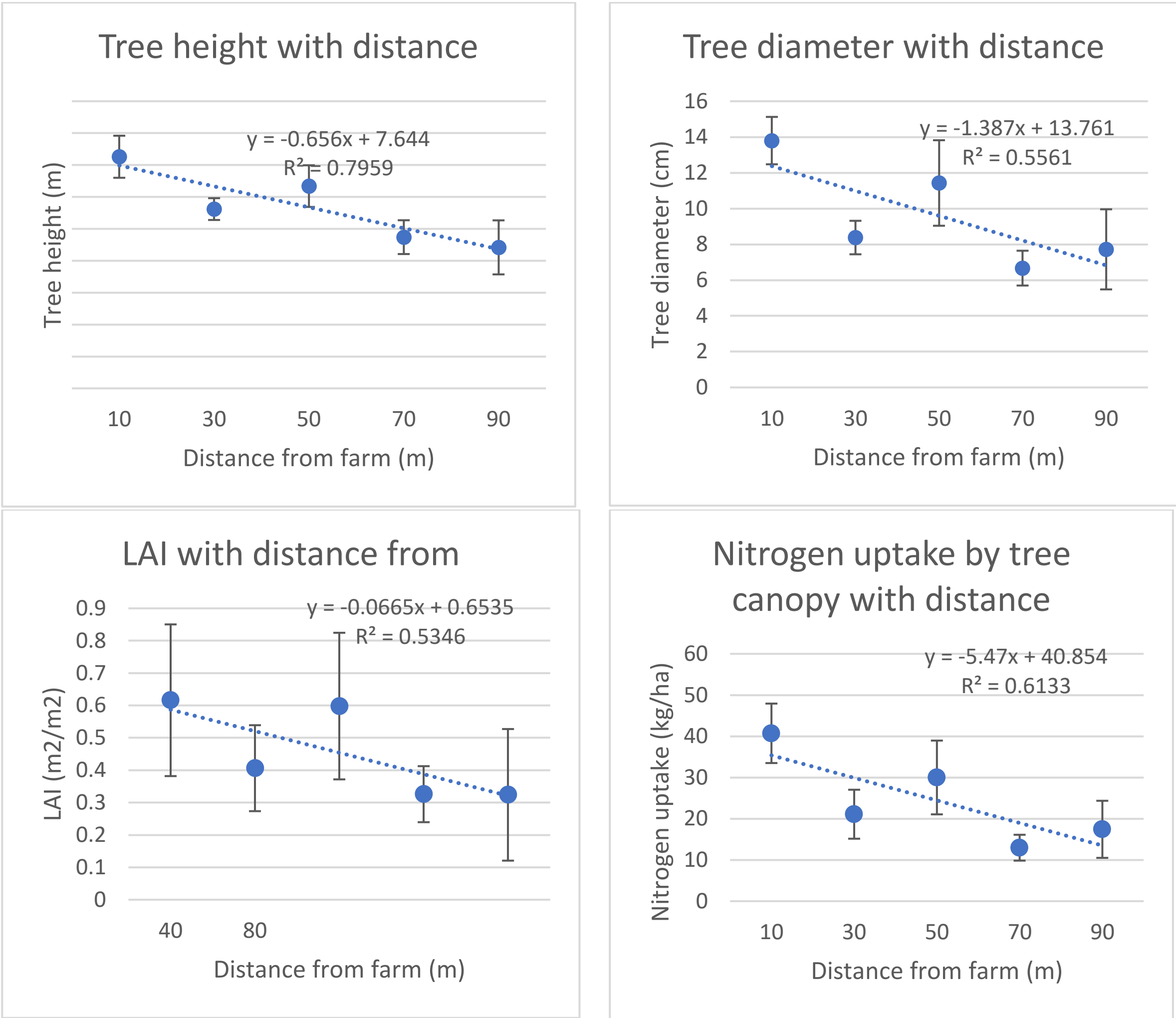


Figure 18: Tree height, diameter, LAI and canopy nitrogen uptake with distance away from Poultry 2 farm. Mean values from 5 to 10 trees of different species for each point in Transect 1 and 2 are presented and vertical bars are standard errors of the mean. Indicative linear relationships are drawn between tree parameters and distance from farm.

Modelling

Figure 19 shows the wind roses for two periods. In Period 2 the wind directions are more mixed and the measured concentrations are less than in Period 3. Period 3 gives mainly southwest wind directions with the ammonia plume coming from the poultry shed most of the time and higher concentrations are experienced. Table ***3*** shows the change in concentration between two sampling points before and after a treebelt (6 to 7) and when no treebelt is present (4 to 5). A third transect was also assessed between points 8 and 9. Having transects between two points of similar length and orientation, one with trees and one without, make for a good comparison. For the transect with no trees (4 to 5) we would expect the modelled change in concentration over the same distance to be similar to the

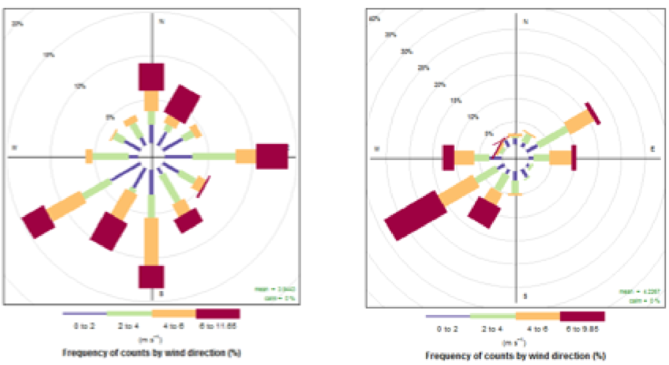


Figure 19: wind roses for Periods 2 and 3 at Poultry 2

change in the measured concentrations. For Period 2 this is borne out as the difference between the respective changes in concentration is relatively small at 2%. The treebelt transect (6 to 7) showed a difference between the model and measurements of 10% to 13% for the two periods indicating a reducing effect on the ammonia plume by the trees. However, we are unable to determine the amount of NH3 that is being taken up by the canopy versus increased dispersion of the plume by the increased turbulence around the treebelt. Interestingly, for transect 8 to 9 the difference between the modelled and measured is negative indicating the decrease in the model is more than in the measured. This could be down to an elevated NH_3 concentration at point 9 caused by a nearby source. This could be either from the fields next to point 9 where some grazing had taken place or the farm to the southwest of Poultry 2.

Table 3: Modelled (SCAIL) vs measured (ALPHA) for Poultry 2 for two periods. The green cell = treebelt between two sampling points. Brown cells = open transect. Period 1 not modelled as no birds in sheds during this period. (units = µg m-3)

Period	Sampling Site	SCAIL	ALPHA	SCAIL % conc △	ALPHA % conc △	SCAIL vs ALPHA
2	1	28.58	22.55			
2	2	4.62	7.64			
2	3	1.91	3.46			
2	4	5.50	11.14	49%	47%	**Difference**
2	5	2.79	5.92			**-2%**
2	6	5.38	9.71	46%	56%	**Difference**
2	7	2.91	4.32			**10%**
2	8	16.45	10.33	82%	66%	**Difference**
2	9	2.97	3.47			**-16%**
2	10	0.46	5.57			
3	1	31.93	53.59			
3	2	8.66	13.87			
3	3	3.67	8.35			
3	4	9.77	52.42	50%	41%	**Difference**
3	5	4.91	31.15			**-9%**
3	6	10.11	52.10	47%	60%	**Difference**
3	7	5.39	20.79			**13%**
3	8	20.86	19.69	83%	74%	**Difference**
3	9	3.45	5.05			**-9%**
3	10	0.95	3.77			

2.3.3 Poultry 3

Figure 20: sampling sites and transects at Poultry 3

Poultry 3 is a former lowland dairy farm that is now used primarily for free range egg production. The main programme of tree planting on the hen ranges was undertaken in 2008 but several additional phases of tree planting have been carried out since then as new units have been built on the holding. The laying unit/shed in Figure 20 with the transect line was used for the study and contained 7,400 organic laying hens. Treebelts for ranging hens are to the northeast between positions 5 to 7 and to the southeast between the shed and sites 8 and 9.

Ammonia Measurements (ALPHA)

NH_3 concentrations between Site 5 and 7 over seven sampling periods (P1-P7) are shown in Figure 21. Periods 3 and 7 had prevailing winds from the southwest, and higher NH_3 concentrations were measured during these periods. Figure 22 compares the concentrations at transects from the shed to site 8 and to site 9, where the transect to site 9 had a gap with no trees, while site 8 had a 40m treebelt between itself and the shed. Over the 7 sampling periods concentrations were always lower in the wooded transect (to site 8) except for period 7 where the prevailing wind was from the southeast. Table 4 show the significance test for periods 1-6 and 1-7. Without Period 7 the difference between the open and wooded transects is significant with 99% confidence limits ($p<0.01$).

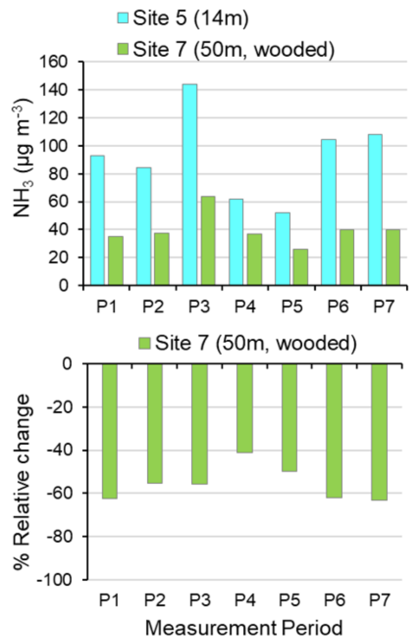


Figure 21: (Top) NH_3 concentrations between paired sites before and after trees at Poultry 3: sites 5 and 7. (Bottom) Relative change in NH_3 concentrations (reference = site before trees), showing large reduction in concentrations (> 81 %) at sites behind the treebelt.

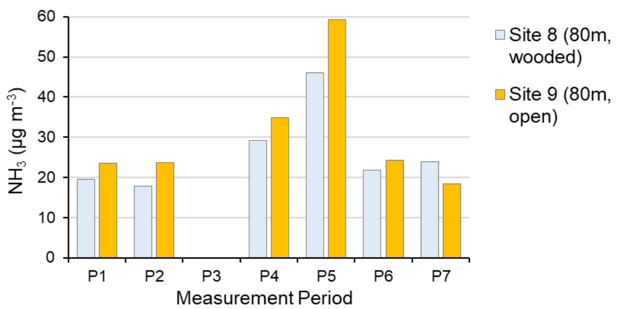


Figure 22: Comparison of NH_3 concentrations between paired sites located at same distance from poultry shed, in a gap in the tree belt (site 9) and behind tree belt (site 8)

Table 4: Poultry 3 NH_3 monitoring: t-test showing significantly larger concentrations at site 9 (in open) compared with site 8 (behind trees) when period 7 is excluded.

	Mean: P1 – P6	**Mean: P1 – P7**
Site 8	26.82 (*n* = 5)	26.33 (*n* = 6)
Site 9	33.11 (*n* = 5)	30.66 (*n* = 6)
Paired T-Test	P = 0.01	P = 0.07

**significant difference at $p < 0.01$*

2.3.4 Intensive Campaign – Poultry 3

Two intensive measurement sites were established at Poultry 3, positioned on either side of a treebelt (23m wide) downwind of a single poultry shed and ranging area (*Figure 23*).

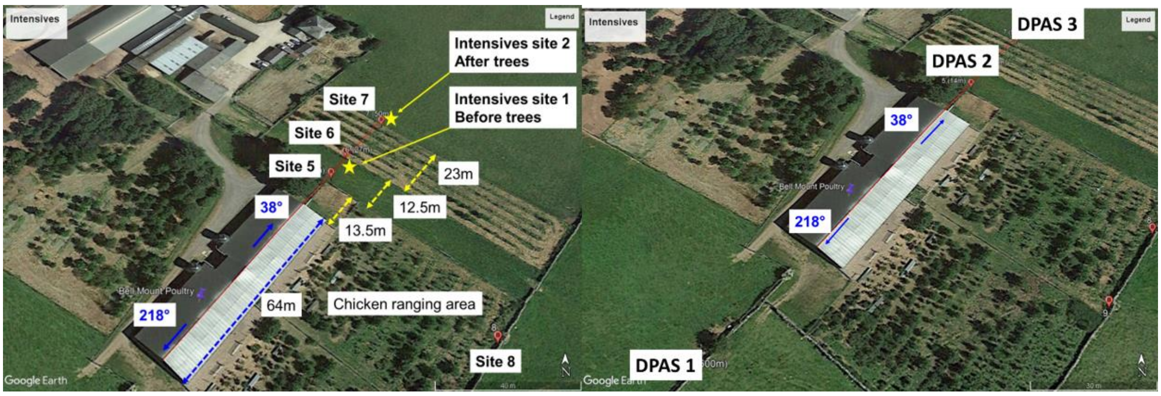


Figure 23 Google earth map of the Poultry 3 Poultry Farm study area, yellow stars showing the locations of the two meteorological and intensive measurement sites; RHS shows the location of the DPAS samplers.

The Poultry 3 Intensive experiment had four main components 1) comparison of UKCE AiRRmonia wet-chemistry instrument vs Los Gatos automatic NH3 gas analysers operated by EA; 2) high resolution measurements of NH_3 and on site meteorology to assess differences between the concentrations before and after the treebelt; 3) high resolution measurements of methane (CH_4), carbon dioxide (CO_2) as tracer gases to determine the relative depletion with NH_3 and provide an estimate of deposition to the trees in the treebelt; and 4) to trial Directional Passive Ammonia Sampler (DPAS) measurements and attempt to detect the reduction in NH_3 due to capture by trees. The 1-minute, high resolution data from one pair of instruments are compared in *Figure 24*. As can be seen in there was good correlation between the two instruments but a significant positive offset (around double) in the Los Gatos Research (LGR) NH_3 concentration which is thought to be due to internal contamination.

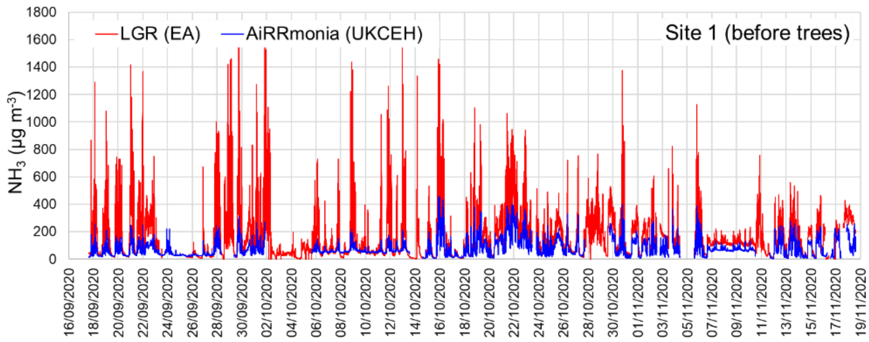


Figure 24: Time series plot comparing high resolution NH_3 measurements on the LGR (EA) and on the AiRRmonia. The LGR NH_3 data appears to read higher than the AiRRmonia.

Figure 25 shows the wind rose (top) and ammonia polar plots (bottom) for the before and after treebelt. The results demonstrate a high correlation between wind direction and ammonia concentrations. The largest concentrations (yellow to red) are to the southwest where the livestock shed was located marked with a star.

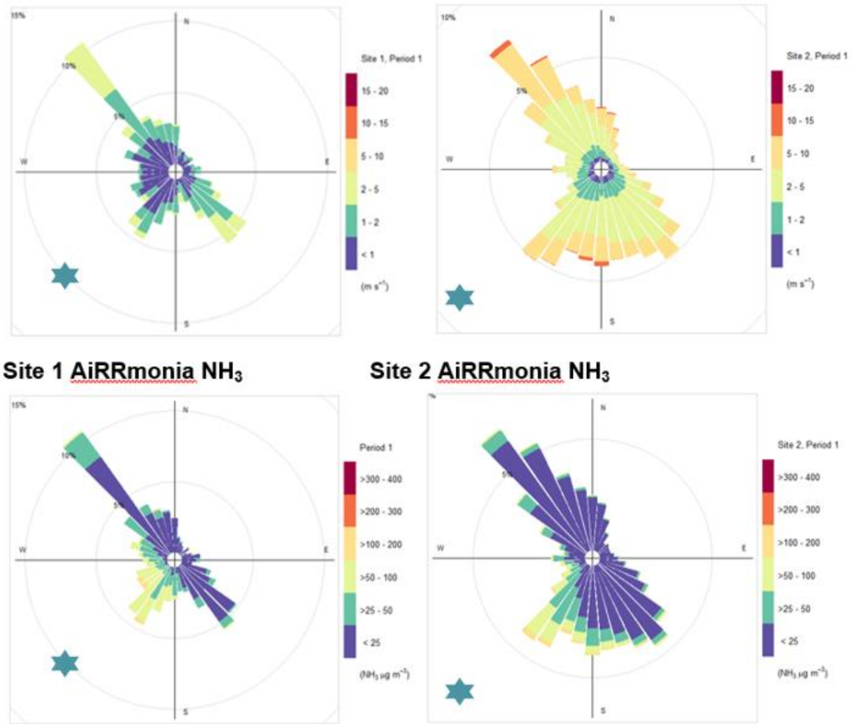


Figure 25: Wind rose and ammonia (AiRRmonia data) polar plots for (LEFT) Site 1 weather station at site 1 before trees (height = 2 m), and (RIGHT) Site 2 weather station at site 2 behind trees (height ~8m). The highest NH3 concentrations are from the directions

A strong diurnal cycle was observed in the NH_3 data from both the LGR and AiRRmonia, and at both sites 1 and 2. Smallest concentrations are in daytime and highest at night-time (Figure 26). This will be primarily due to diurnal changes in the boundary layer height, meteorological conditions and the farm management of the poultry (kept in at night).

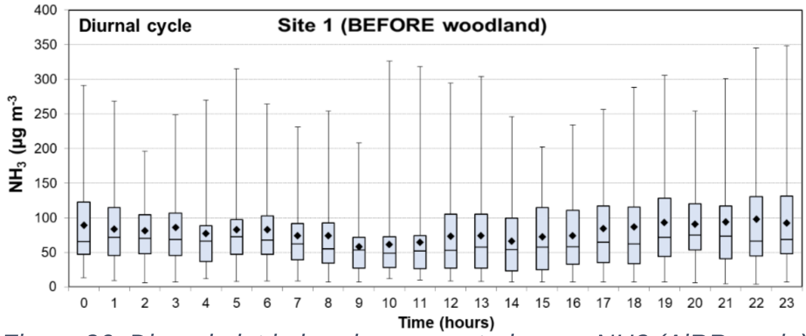


Figure 26: Diurnal plot in hourly aggregated mean NH3 (AiRRmonia) at site 1 over the period 16/09/2020 to 18/11/2020. This shows a strong diurnal pattern, with smallest concentrations during the daytime and rising at night time.

When DPAS results were first examined it was clear that the sampler had not aligned with winds that were light and/or of short duration, so some samples were compromised. A procedure was applied to "screen out" periods and sectors with such winds. Improvements to the DPAS have been proposed to resolve the alignment issue in future.

DPAS data for "screened in" periods/sectors at the **before trees** and **after trees** sites were compared with adjacent automatic data. The average concentrations for 14 periods/sectors using measured winds were 51.2 and 51.6 ug/m^3 from DPAS sampling and automatic data, respectively. A similar comparison for 9 sectors/periods using modelled winds gave average concentrations of 39.6 and 36.9 ug/m^3 from DPAS sampling and automatic data, respectively. Another comparison showed that DPAS and automatic data agreed within ~5% for concentrations averaged over 1-4 sectors for a ~2-week period.

Reductions in ammonia fluxes and concentrations were evaluated between the **before trees** and **after trees** positions of DPAS-MANDEs at the 6000-bird shed. Percentage reductions were evaluated using screened-in data for 30^o sectors averaged over 4-6 weeks, and were similar for fluxes and concentrations. The percentage reductions in fluxes for specific transects were (Figure 27):

- ~25% for airflows from a 30^o sector downwind of the shed, after crossing 25m of trees.
- ~40% for airflows from a 90^o arc that covered the shed and ranging area, after crossing 27m of trees.
- ~70% for airflows from a combined 30^o/60^o arc from the ranging area, after crossing 28m of trees.
- ~50% for airflows from a 120^o arc covering all poultry activities, after crossing 31m of trees.

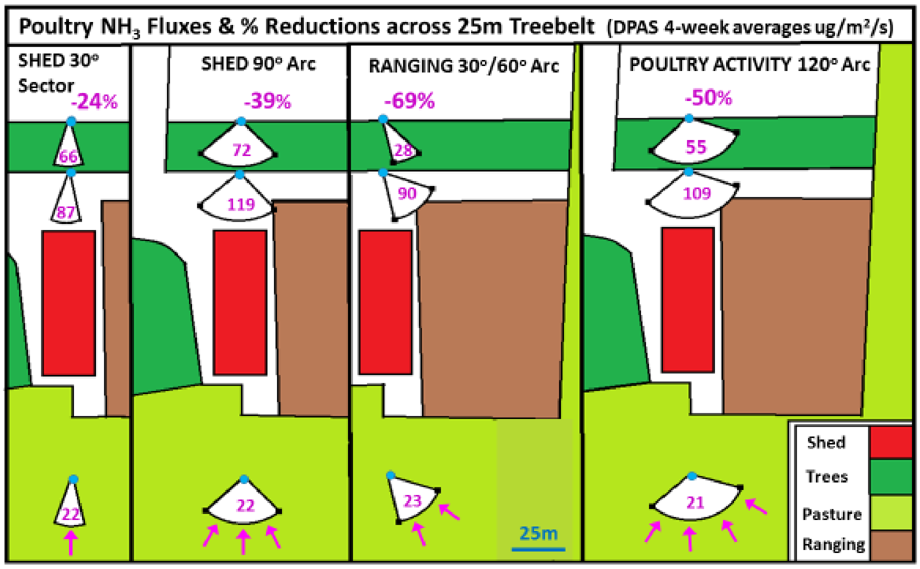


Figure 27: Poultry ammonia fluxes (ug/m²/s) and percentage reductions across 25m of trees for 4 transects at the 6000-bird shed: 4-week-averages for individual and combined 30º sectors from DPAS sampling

The lower rate of reduction for the shed airflows compared to the ranging area airflows (-24% compared to -69%), was probably because of different heights of emission. Ammonia from the shed is emitted from its eaves at ~3m above ground, so that some may pass over the trees without being intercepted. By contrast, ammonia from the ranging area is emitted at ground level and so is more likely to be intercepted by trees.

In order to make like-for-like comparisons between amounts of ammonia reduction by trees, the percentage reductions for different transects were normalised to a consistent tree depth of 25m. The lowest normalised reduction was about 20% for ammonia in well-mixed background air, and the highest was ~60% for ammonia from the ranging area (Table 5). The amounts of normalised reductions for other transects lay conformably between these lowest and highest values, which suggested that the DPAS-MANDE system has provided plausible estimates of ammonia reduction by trees.

Table 5: Percentage reductions by trees in NH3 fluxes and concentrations: summary for different transects showing emission height, distance through trees and reductions normalised to 25m (4-6 week averages).

Transect			% Reduction in Flux		% Reduction in Concn.	
Description	Emission height	Distance through trees	Un-normalised for distance	Normalised to 25m	Un-normalised for distance	Normalised to 25m
Shed 30º Sector	3m (eaves)	25m	-24%	-24% *	-24%	-24% *
Shed 90º Arc	0-3m (variable)	27m	-39%	-36% *	-39%	-36% *
Overall 120º Arc	0-3m (variable)	31m	-50%	-40% *	-50%	-40% *
Ranging 30º/60º Arc	0m (ground)	28m	-69%	-62% *	-70%	-63% *
Background 30º Sector	n/a (well-mixed)	65m	-50%	-19% #	-56%	-22% #

*Reduction due to interception by 25m of trees and plume dispersion over 25m.

Reduction due to interception by 25m of trees only.

2.3.5 All Farms - Species effects of tree growth, leaf morphology and nutrient uptake

Averaged tree parameters for all farms were calculated and are presented in Figure 28 to Figure 31. Similar tree species were covered in all farms as much as possible.

Tree height and diamater were in the order of highest at Dairy 2 > Poultry 2 > Poultry 3 > Poultry 1 > Poultry 4 likely corresponding to the planting age of the trees within the treebelts at the farms. Tree height and diameter varied significantly between tree species with a tree height range of 3.5 to 8.6 m and tree diameter range of 3.5 to 18 cm.

LAI (Leaf Area Index) varried greatly with tree species, with the average range of 0.1 for hawthorn to 2.5 m^2/m^2 for Poplar. Poplar, Elm, Ash, Birch and Willow growth was significantly higher compared to other tree species. Tree canopy uptake of nitrogen ranged between 1.5 to 50.5 kg N/ha. Poplar, Willow, Oak, Ash, Alder, Birch and Elm canopy nitrogen uptake ranged betwee 20-50 kg N/ha compare to other species where nitrogen uptake was <20 kg N/ha. Variability in tree growth of different species is due to differences in tree spcies ages at the different farms, but also potential difference in soil type and nitrogen supply to trees.

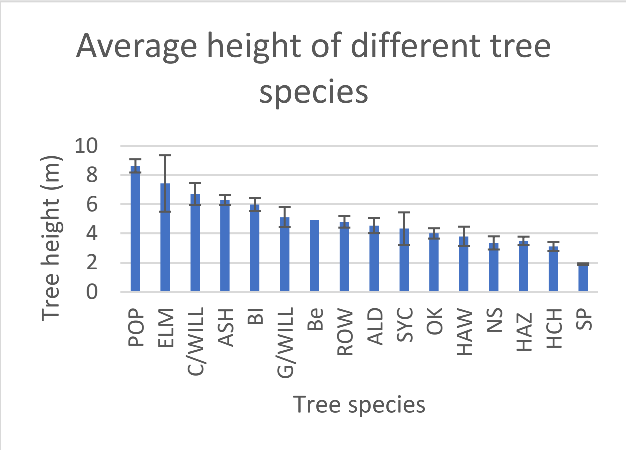


Figure 28: Tree height per tree species measured across all farms. Bars are mean values for height for each species measured from all sites and vertical lines are standard errors of the mean.

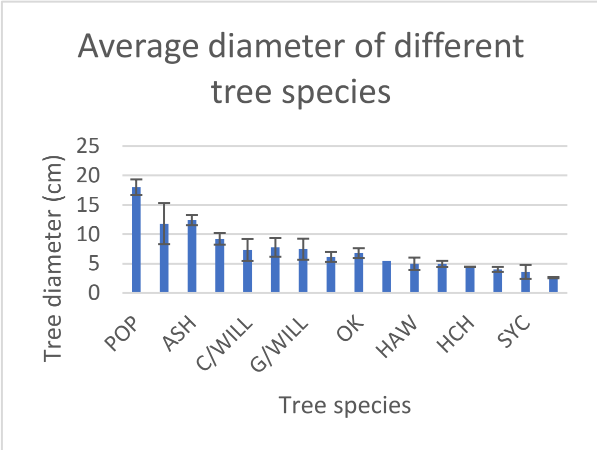


Figure 29: Tree diameter per tree species measured across all farms. Bars are mean values for diameter at breast height for each species measured from all sites and vertical lines are standard errors of the mean.

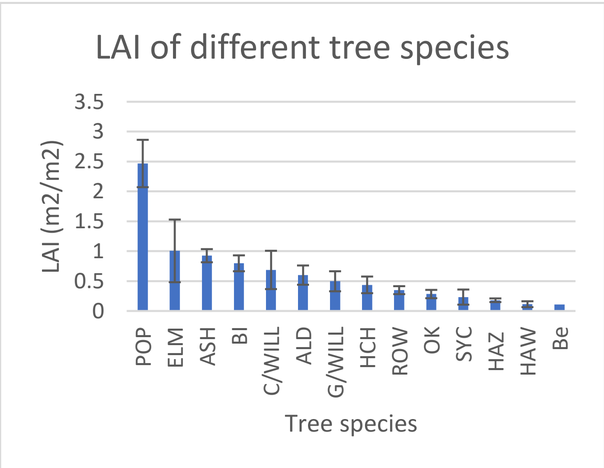


Figure 30: Leaf Area Index (LAI) for different tree species measured across all farms. Bars are mean values for LAI for each species measured from all sites and vertical lines are standard errors of the mean.

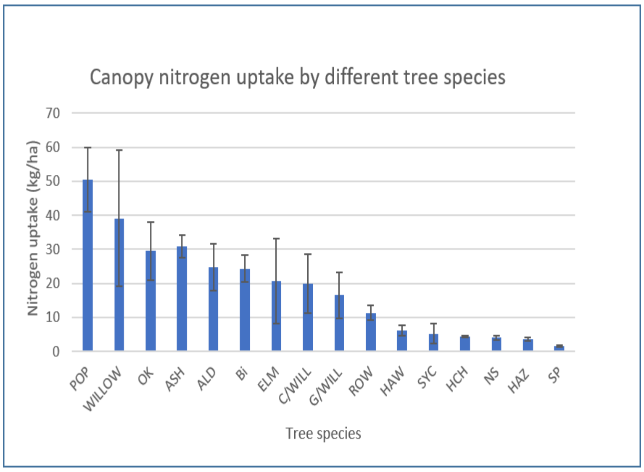


Figure 31 Canopy nitrogen uptake by different tree species measured across all farms. Bars are mean values for canopy nitrogen uptake for each species measured from all sites and vertical lines are standard errors of the mean.

2.3.6 Estimate of treebelt recapture of ammonia plume

NH_3 is highly reactive and water-soluble with an atmospheric lifetime of a few hours. CO_2 and CH_4 have longer lifetimes, with low solubility in water. CH_4 and CO_2 can therefore be used as conservative tracers, with the assumption that they decline with distance due to meteorology, with no uptake by trees. The hypothesis is that there will be minimal deposition of CO_2 and CH_4 to the treebelt compared with NH_3, which will cause the ratio of the air concentration of NH_3 to that of CO_2 and CH_4 to decrease with distance away from the source.

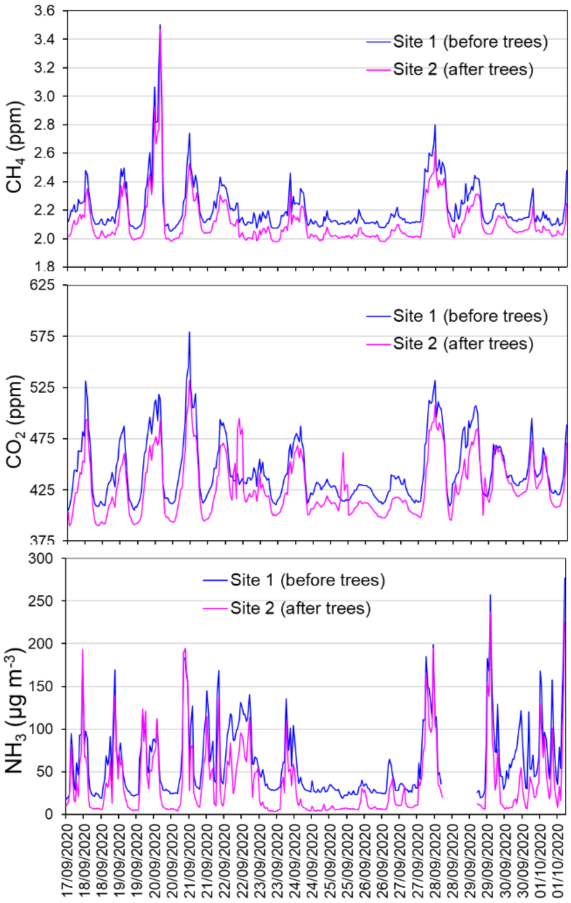


Figure 32: [CH4], [CO2] and [NH3] profile downwind of poultry housing, before and after treebelt.

The peak periods in CO_2 and CH_4 concentrations coincides with maximum concentrations of NH_3 Figure 32. Using the one-minute meteorological data from site 2 and the measured concentrations of the gases, a fractional depletion due to uptake of NH_3 by the trees was between 0.3% comparing CH_4 to 6 % using CO_2. This has a high uncertainty due to the relatively small fraction of data which met filter criteria (WS > 2 m s^{-1}, WD = 200 - 250^o, all analyser operational; 1969 data points out of ~80000 in campaign).

Modelling was carried out using the coupled turbulence-deposition model Moddas-OpenFoam. LAI, height and treebelt depth are key determinants for ammonia recapture and input data were determined from survey work undertaken by Forest Research, except for Dairy 2 where height of canopy and LAI were estimated from aerial photography and estimated age of the trees. Percentage canopy capture are expressed as an annual capture with an estimate of seasonal LAI taken into account. The percentage capture ranged from 80% (Dairy 2) to 0.1% (Poultry 4) Table 6. In the case of Dairy 2 a high (estimated) LAI and height, and deep canopy results in a very high capture of 80%. Short treebelts E.g. at Poultry 3 (23 m) give rise to low % capture, although the LAI at Poultry 3 was the highest in the group of farm-planted treebelts. The treebelt canopy at Dairy 1 with a treebelt depth of 170 m gave just over 4%. For the young treebelt of around 5 years of age at Poultry 4 the ammonia capture is negligible, as the height of trees was less than 3 m with an associated very low LAI (0.06).

Table 6: Moddas-OpenFoam results for 8 tree treebelts across 5 farms

INPUT DATA	**Poultry 1 (Fans)**	**Poultry 1**	**Poultry 2**	**Dairy 1 (Poultry shed)**	**Dairy 1 Dairy (shed)**	**Dairy 2**	**Poultry 3**	**Poultry 4**
Emission Strength (NH_3 tonnes per year)	3480	4060	3480	4640	10366	7774	1740	9280
Height of shed (m)	5	3.6	3.6	3.6	4	4	3.6	3.6
Length of shed (m)	80	50	80	100	45	50	65	20
Area of Shed (m^2)	1630	1800	1772	2000	1350	5836	1270	4400
Distance from shed to main canopy (metres)	25	15	35	7	40	36	26	45
Main canopy depth (m)	100	137	33	36	170	330	23	65
Main Canopy Height (m)	5.04	5.04	5.66	6.11	6.11	16.1	5.36	2.57
Main Canopy LAI (From FR - except. Dairy 2)	0.79	0.79	0.45	0.83	0.83	3.10	0.95	0.06
Backstop (m)	0	0	0	0	0	0	0	0
TOTAL	**-1.0**	**-1.6**	**-1.3**	**-2.8**	**-4.2**	**-80.6**	**-1.7**	**-0.1**

As trees grow they gain height and subsequently increase their canopy and LAI which give rise to higher ammonia capture. Treebelts planted for ranging livestock are unlikely to capture significant amounts of ammonia in the first 5 years. It is noted that none of the treebelts were planted for the purpose of reducing NH_3 emission to the atmosphere via recapture.

2.4 Conclusions

- Across the spectrum of experiments carried out in this project, it can be shown that the trees have an effect on the NH_3 plume from livestock housing and that there are interactions with the treebelt through nitrogen deposition and dispersion effects. This demonstrates the potential for NH_3 mitigation as treebelts mature, and that strategically planted treebelts in the landscape can mitigate NH_3 concentrations locally to protect sensitive semi-natural sites downwind of livestock housing, plus take some NH_3 emitted out of the atmosphere though recapture. This in conjunction with other benefits mean that ammonia recapture by trees is part of the toolkit of solutions for reducing N pollution.
- At Poultry 2, a paired set of sampling sites located at the same distance with and without (open) trees was used to look at the difference a treebelt would make on the NH_3 concentration. A significantly larger reduction in NH_3 (-59%, $p = 0.02$) was observed at the monitoring point behind the treebelt, compared to the open transect (-40%), likely due to increased dispersion and vegetation capture. The results confirm previous studies that tree treebelts cause NH_3 concentrations to decline more rapidly with distance from the poultry housing compared with open (treeless) land.
- A high-resolution monitoring approach with NH_3 and CO_2 tracer has significant potential to be used with meteorology to understand in detail the impact of sources on farming landscapes and integrate carbon and nitrogen footprints. A mix of surface concentrations and at a downwind elevated location for flux measurements would be optimal, and should be tested at exemplar farms for improving metrology protocols for this type of study
- Tree height is a less variable measurement of tree growth compared to tree diameter at a young stage of tree growth. Thus, tree diameter is a more representative parameter, taking account of the variability between tree species and its use in developing model allometric relationships such as the diameter/foliage biomass relationship used to underpin the LAI calculations.
- From the literature, fast growing tree species such as Poplar, Willow, Birch and Ash take up significantly higher (at least double) amounts of nitrogen, compared to slow growing tree species such as Rowan, Hazel, Sycamore, demonstrated by the results from this study.
- Using CH_4 and CO_2 as conservative tracers for NH_3, a fractional depletion due to uptake of NH_3 by the trees was estimated to be between 0.3 - 6 %. This has a high uncertainty due to the relatively small fraction of data which met filter criteria (WS > 2 m s-1, WD = 200 - 250°, all analyser operational; 1969 data points out of ~80000 in campaign).
- Results from the DPAS-Mande showed that ammonia concentrations from a 30° sector that mainly covered the shed were reduced by about 25% between the "Before Trees" and "After Trees" positions.
- For most of the farm treebelts, the change in the measurements (2-weekly) before and after the treebelts were higher than in the modelled runs, suggesting the trees are having an effect on the NH_3 plume through canopy dispersion (increased turbulence and mixing) and deposition (capture and uptake by trees).

3 WP3: Farmer's views on practicalities and farm business benefits of tree planting to mitigate ammonia

[Authors: Jan Dick & Bill Bealey]

3.1 Scope

To gauge the views of farmers on the practicality and benefits of using treebelts to mitigate ammonia on their farms, interviews were conducted with farmers from the 5 case study farms supplemented by a wider online survey.

3.2 Approach

For five case study farms two interviews were conducted, one before and one after data and information on the effectiveness of treebelts at mitigating ammonia emissions on their farms was shared. The interview protocol consisted of 22 questions adapted from the ADOPT model (Adoption and Diffusion Outcome Prediction Tool[6]). This tool was selected as it explicitly addresses the motivation of farmers, relative advantages of a new innovation (such as planting trees to mitigate ammonia) and the learning associated with the new innovation. Both qualitative (narrative) and quantitative (Likert scale) data was documented for each of the 22 questions. In the second interview, 16 of the original questions were asked again plus five additional questions focused on the interviewees' opinion of the ammonia tree calculator and guidance documentation (www.farmtreestoair.ceh.ac.uk). A further larger online survey of broader farm types was carried out between 22nd March 2021 and 24th April 2021 based on the same 22 questions.

3.3 Results

3.3.1 Farmer 1:1

Figure 33 shows the average scores of the five farmers for the questions focused on the relative advantage of the practice of planting treebelts for ammonia mitigation. There was a realisation amongst all farmers interviewed that planting trees to capture ammonia was a relatively new concept and woodland was yet to be proven to capture significant quantities of ammonia from hen and dairy enterprises. All farmers scored profit orientation relatively high as a motivation for planting trees with one commenting: *it's not a profit from the wood, but I do get paid for having the trees for cover for the hens.* Another farmer remarked that the woodland on their farm was grant aided adding *our motivation was to improve the environment generally - not specifically for ammonia capture but better environment makes the farm more resilient.* However, environmental impacts scored the highest average score as all farmers saw this as a key benefit, while the ease and convenience of planting treebelts was a negative advantage i.e. a disadvantage. Risk minimisation was also seen as an important consideration for adopting the practice as it was a stipulation in their egg contract and thus linked to their profit motivation. The questions focused on the ability to learn about the practice (Figure 34) highlighted that the interviewed farmers

[6] https://adopt.csiro.au/

considered advisory support and group involvement more beneficial than practice awareness which scored lower.

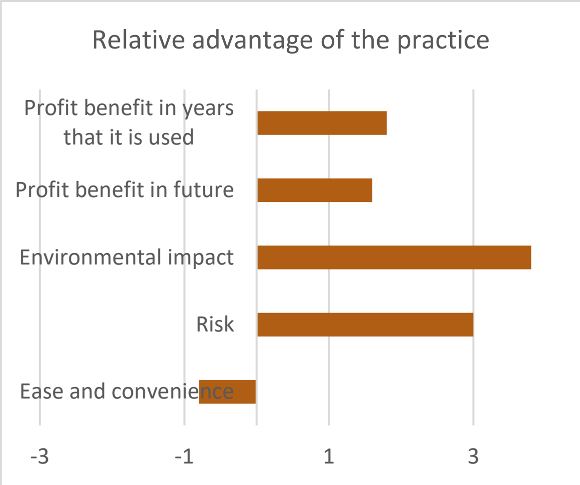


Figure 33: Mean score (n=5) for questions in ADOPT model answered in interview 1 focused on the relative advantage of the practice on a scale of -3 to +4.

Figure 34: Mean score (n=5) for questions in ADOPT model answered in interview 1 focused on farmer-specific influences on the ability to learn about the practice.

Generally, the farmers interviewed consider the "Learnability characteristics of the practice" i.e. trialling ease, practice complexity and observability as relatively low at the first interview. The farmers found it strange to consider tree planting for a single aim. One farmer summed up the possibility of trialling tree planting to capture ammonia before fully committing to the practice as *not very easy to trial - we have a lot of trees - we did not plant for ammonia capture*. While another echoed the earlier comments about the long-term nature of trees *…trees are a long-term thing. You just got to get on it. In my view, you can't really try trees.*

The difference in the mean score for repeat questions asked in the second set of interviews are presented graphically in Figure 35. The average scores for all repeat questions was higher or very similar in the second interview after the farmers had access to data detailing the capture of ammonia on their farm, the ammonia calculator and the guidance document, indicating that increased knowledge about the role of trees to capture ammonia resulted in a higher probability that they would adopt the practice.

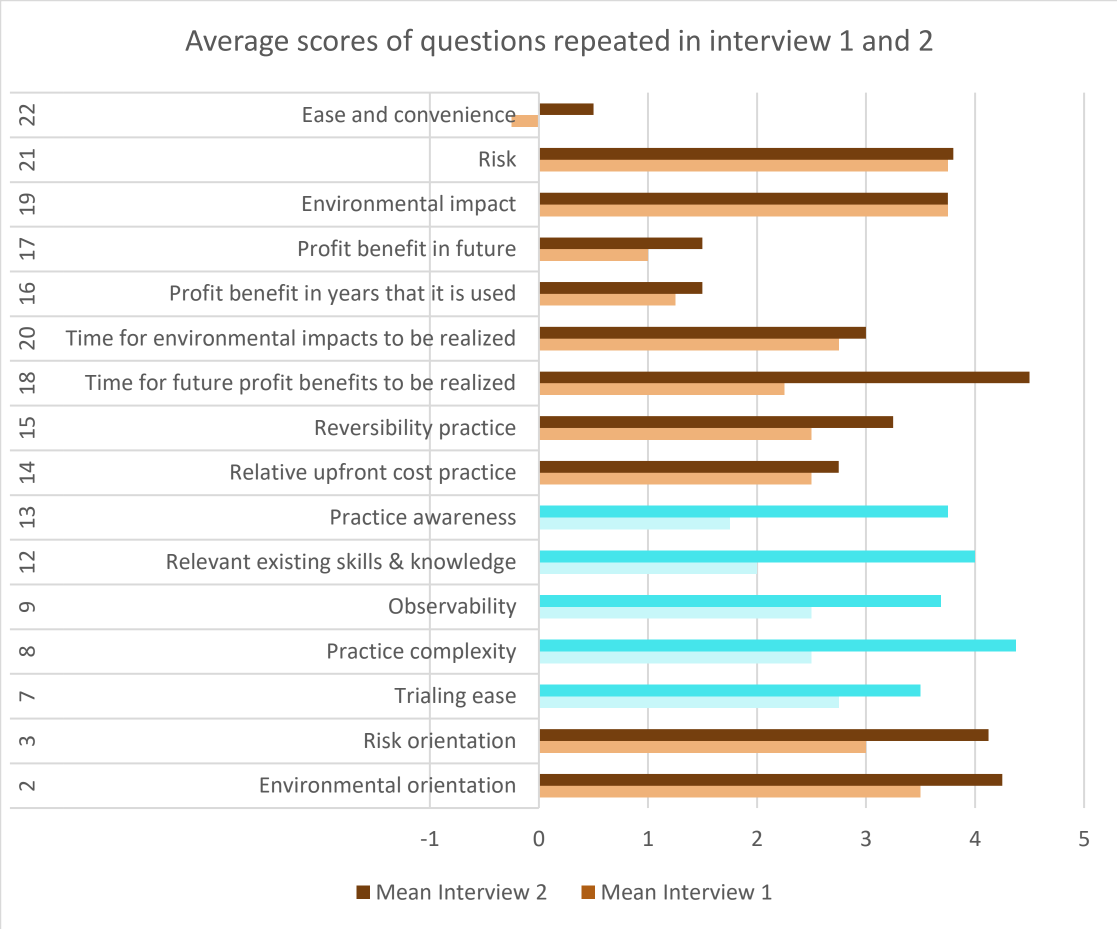


Figure 35: Mean score (n=4) for repeat question in interview 1 and 2. Top bar, darker colour, indicates results from second interview; green indicated the question related to the relative advantage of the practice and blue the learning characteristics.

In addition, to the sixteen questions which were a repeat from the first interview, farmers were asked four questions related to their opinion of suggested improvements to the calculator and one related to the guidance document (Figure 36). All farmers interviewed agreed or strongly agreed that the guidance document was helpful (average score 4.5). One farmer commented that they appreciated being led through the document, which raised the possibility of a video presentation of the main points being easier than reading alone. Another farmer commented that a clearer list of principles would be helpful *It's a long document ...An absolute checklist of things to do would be easier than having to run through all of the text.*

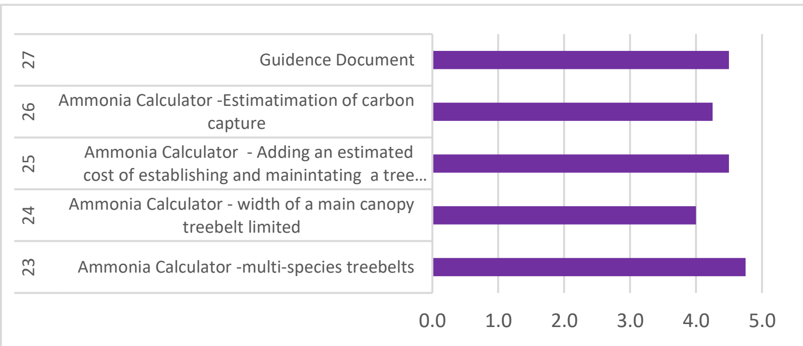


Figure 36: Interviewees (n=4) opinion of the guidance documentation and aspects of the ammonia-tree calculator.

The ammonia calculator was demonstrated to three of the farmers at the start of the interview and the fourth had seen it several times during development. He commented that *the new version has a lot more help ... the question mark icon is really useful.*

3.3.2 Online Survey

In total 148 responded to the online survey with the breakdown of farmer type based on the self-reported enterprises on their farms shown in Table 7.

Table 7: Number of respondents grouped hierarchically into four categories dairy, pig, poultry, or beef/sheep enterprises dependant on the farm enterprises reported.

Farm type	Number of respondents
Poultry	69
Beef/Sheep	37
Pig	26
Dairy	16
Grand Total	148

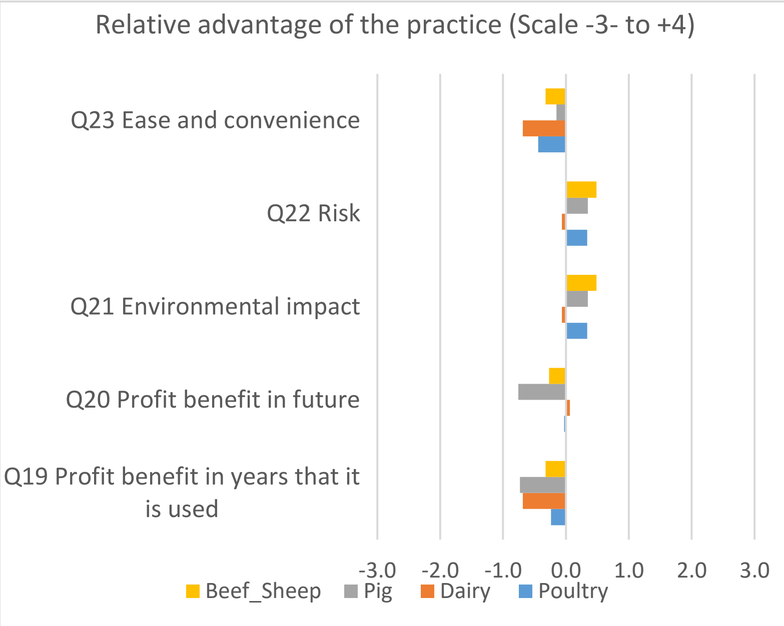


Figure 37: Average score of -3 to +4 for advantages of planting trees for ammonia mitigation for profit, risk, the environment and ease of implementation n=148 farmers.

Negative score of -3 represented 'Large disadvantage' while +4 was a 'Large advantage'. From Figure 37 the bar-chart shows profit and ease and convenience of implementation all on average had negative scores, all be it only slightly negative (< -1), while environment and risk were scored positively. It is interesting that risk scored positively (some reduction in risk) while profit was negative. The dairy sector was neutral on risk and environmental impact while most strongly negative for ease of convenience of implementation, possibly representing some of the advance that the pig and poultry industry have already put into ammonia mitigation.

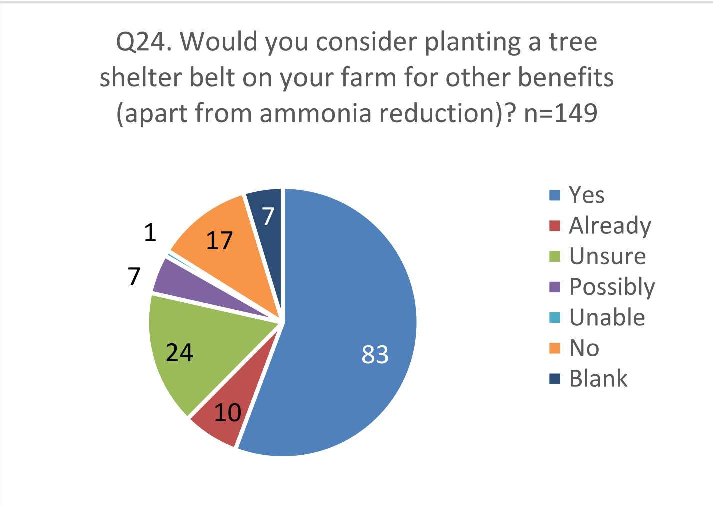


Figure 38 shows that 56% responded positively (n=83), while 6% have already planted trees (n=16). Only 11% were negative in this response with others 'unsure' (16%) or 'possibly' (5%).

Figure 38: Answers based on the question 'Would you consider planting a tree shelter belt on your farm for other benefits (apart from ammonia reduction)?'

From Figure 39 the majority (54%) suggested that environmental benefits were the main benefit. This included biodiversity/wildlife, carbon sequestration, and ammonia reduction as the main environmental benefits. Animal welfare through ranging and sheltering were seen as the next best benefit from treebelt planting (13%).

Figure 40 below that the overwhelming motivation concerned financial support (61%) to carry out tree planting either via grants, payment for capital costs or incentives.10% were motivated by the environmental benefits and 5% had already planted trees on their farm.

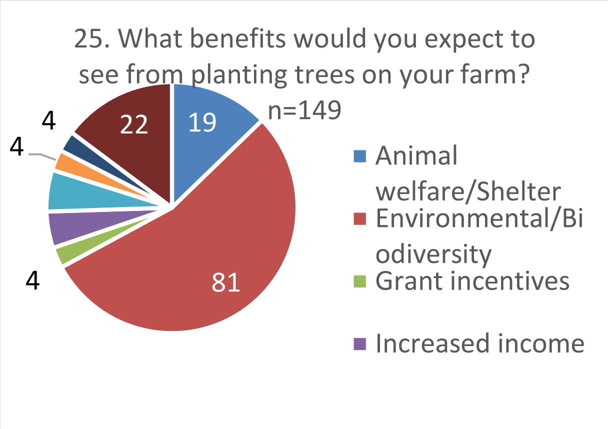


Figure 39: Answers based on the question 'What benefits would you expect to see from planting trees on your farm?'

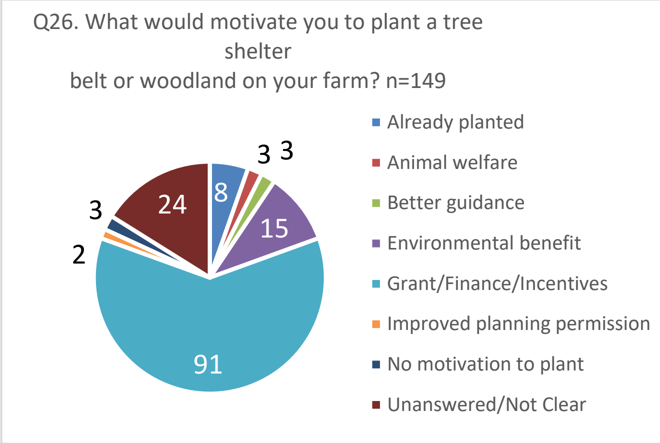


Figure 40: Answers based on the question 'Q26. What would motivate you to plant a tree shelter belt or woodland on your farm?'

3.4 Conclusions

The 22 questions of the ADOPT model was found useful in this study as they provided a structured framework that incorporated and highlighted factors, information and principles known to be important to adoption outcomes of agricultural practises in developed countries.

From the analysis of the survey data from the model it was clear that providing knowledge and guidance on the use of treebelts to reduce ammonia gave a potential higher level of adoption of the practice and a shorter time to adopt. Following presentation of ammonia data from their farms, the ammonia calculator and the guidance document, the farmers were convinced that their trees did in fact capture ammonia. Parameterised with the data from the first interview the ADOPT model estimates that 45% of farmers would take up the practice. However, if the positive attitude resulting from increased knowledge was replicated thought out the farming population the ADOPT model predicts that adoption of the practice would peak at 85% of the population. Time to near peak adoption level would reduce from 18 years to 10 years with increased knowledge.

Gaining finance or grants to cover the cost for planting were seen as the most limiting factor for being motivated to plant treebelts on their farm (over 60% of respondents said this). Further limitations were the time for future benefits and profits to be realised and the risk of changing farming practice to a much longer-term commitment of planting treebelts.

The online survey gave similar (often the same) ADOPT scores across the 22 questions but scored much lower for questions around risk, knowledge and profit - represented by higher risk, lower knowledge and lower profit advantage. As a consequence, the adoption peak level was only 2%, with a 15-19 year time to near peak adoption period. Farmers stressed that woodland creation was multi-purpose and planting designs should have multiple purposes, and considered incentive schemes should enable flexibility so farmers can maximise the benefit of tree planting to their specific environment and to fit their business objectives.

BANGOR
UK Centre for Ecology & Hydrology
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW
United Kingdom
T: +44 (0)1248 374500
F: +44 (0)1248 362133

EDINBURGH
UK Centre for Ecology & Hydrology
Bush Estate
Penicuik
Midlothian
EH26 0QB
United Kingdom
T: +44 (0)131 4454343
F: +44 (0)131 4453943

LANCASTER
UK Centre for Ecology & Hydrology
Lancaster Environment Centre
Library Avenue
Bailrigg
Lancaster
LA1 4AP
United Kingdom
T: +44 (0)1524 595800
F: +44 (0)1524 61536

WALLINGFORD (Headquarters)
UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
United Kingdom
T: +44 (0)1491 838800
F: +44 (0)1491 692424

enquiries@ceh.ac.uk

www.ceh.ac.uk