UK Centre for Ecology & Hydrology

Ammonia Reduction by Trees (ART)

Field case studies for monitoring ammonia reduction by treebelts

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Executive Summary

- Five farms were identified which had existing trees in proximity to intensive livestock units to undertake ammonia (NH_3) and ecosystem measurements and apply simple atmospheric modelling of NH_3 the sites.
- The work consisted of four components
    1. Spatial NH_3 measurement (2-weekly) and ecological surveys.
    2. Intensive measurements with high resolution NH_3, Carbon Dioxide (CO_2), Methane (CH_4) and Particulate Matter (PM) analysers and on-site meteorology on either side of a tree treebelt at Poultry 3 farm.
    3. Trialling of new design EA/University of Lancaster Directional Passive Ammonia Samplers (DPAS).
    4. Use of screening tool model (SCAIL) and treebelt model (MODDAS) to compare measurements with modelled.
- The purpose of this work was to collect:
    - Spatial NH_3 and ecosystem datasets, where treebelts were present close to the emission source for model testing and validation.
    - Evidence of NH_3 concentration differences between open (no tree) NH_3 concentrations and where there were trees, including one or two sites equidistant with open and tree transects.
    - Where ecological measurements were co-located, to compare the indirect evidence this measurements provided.
    - Use of SCAIL-Agriculture to predict concentrations without trees and assess the difference between modelled and measured.
- Monitoring of atmospheric NH_3 concentrations was carried out August - November 2020 at five case study farm: three poultry (free-range layers), one dairy and one mixed (dairy + poultry)
- Each farm was selected because they had existing woodland planting (including sites based on the design tool), with different age and depth of treebelts and contrasting size and orientation of livestock housing to the prevailing wind.
- A total of 10 two-weekly measurement periods were planned, but were reduced to 5 - 8 measurement periods due to the UK outbreak of avian influenza.
- Trees height and diameter were measured, foliar sampling from trees along transects away from farms. Leaf morphological traits and chemistry were measured by Forest Research
- A lichen survey, from sampling branches of birch (Betula spp.) and oak (Quercus spp.), was conducted at sampling points along transects up to 450m from the farm buildings, at two study farms: Dairy 1 farm (dairy and free-range hens in a tree treebelt) and Dairy 2 farm (dairy farm with mature woodland).

Key findings and recommendations

- 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.
- The intensive experiment, despite being limited in duration, showed the benefits of having measurement validation of modelled NH_3 uptake by trees. This type of measurement approach will be particularly important for constraining uncertainty in future, where evidence gathering for landscapes with complex ammonia emissions.
- A high resolution approach with NH_3 and CO_2 tracer has significant potential to be used with meteorology to understand in detail the 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
- It is recommended that these 5 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.

Farm Ammonia monitoring

- Passive ALPHA® samplers provided spatial and temporal NH_3 concentrations around each of the 5 farms. Upwind "background" NH_3 concentrations in this Cumbrian landscape ranged between 4 $\mu g\ m^{-3}$ (Poultry 2) and 18 $\mu g\ m^{-3}$ (Poultry 4 / Poultry 3).
- The largest NH_3 concentrations were detected at monitoring locations in the closest proximity to the poultry or cattle sheds, but declined rapidly with distance downwind through the trees to background levels at 150 – 300 m from housing source. Decreases in NH_3 concentrations with distance from source occur due to dilution from atmospheric dispersion and removal processes from surface/vegetation uptake (which would include capture by trees).
- NH_3 concentrations in close proximity to animal housing were 10-200 times higher than the Critical Level of NH_3 concentrations for higher plants of 3 $\mu g\ m^{-3}$ (annual mean) and 30-600 times higher than the Critical Level of concentrations for lichens & bryophytes of 1 $\mu g\ m^{-3}$ (annual mean).
- At Poultry 2, a paired set of sampling sites located at the same distance with and without trees (open) 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 land.

- At Dairy 1, 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 capture NH_3 from the dairy farm and grazing emissions from the fields. 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).
- At mixed Dairy 1, results indicated that the treebelt is dispersing and/or capturing NH_3 from the poultry sheds and dairy buildings, as NH_3 concentrations declined more rapidly with distance (on average 16.6 % smaller) from the livestock housing across the wooded transect (mean concentration of 18 µg NH_3 m^{-3}) compared with open transects (mean concentration of 21.5 µg NH_3 m^{-3}).

Ecological measurements

- Findings from this research suggest that the trees have been growing faster nearer to the farms where NH_3 concentrations were higher. Results also suggest that trees were accumulating higher concentration of nitrogen and have higher canopy nitrogen uptake in their canopies nearer the livestock sheds where NH_3 exposure was higher.
- There is clear evidence that tree growth is significantly higher nearer the farms and decline with distance away. This is very likely to be related to the decreasing gradient of NH_3 concentrations which was observed with distance away from the farms made in this 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 and the results from this study demonstrate this
- Trees with higher LAI adsorb higher amount of nitrogen in their canopies.
- Trees in this study showed enhanced growth compared to trees further away.
- Overall results suggest that treebelts planted in the vicinity of poultry and dairy farms have potential for both NH_3 mitigation and increased carbon sequestration.
- Lichen species diversity and presence/absence is an indicator of the level of N deposition, with N tolerant species dominating where N pollution has been high for an extended period. At these farms, using the presence/absence of target lichen species on tree show low diversity of lichen flora at the two sites, and the floras estimate a high level of nitrogen deposition in both areas including the

control sites. NH_3 is slightly lower at the control sites but above critical levels. In the NH_3-high landscape emissions from the two farms are affecting the lichen flora.

- 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.
- There were complications introduced by the difficulty of finding suitable tree species for the study and the influence of woodland cannot be confirmed.

Intensive measurements at one site

- High resolution NH_3 data at Poultry 3 intensive sites 1 and 2 showed large variability in the range of between 3 – 457 NH_3 µg m^{-3}.
- A comparison of NH_3 data from parallel measurements with the co-located AiRRmonia wet chemistry instrument and the LGR automatic gas analyser at both sites show indicative differences. NH_3 concentrations measured by the LGR were approximately 10-fold and 2-fold higher than the co-located NH_3 data from AiRRmonia at site 1 (before trees) and site 2(after trees), respectively.
- A strong diurnal cycle is 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. This will be primarily due to diurnal changes in the boundary layer height, meteorological conditions and the farm management of the poultry emissions. Diurnal cycles are also observed in CO_2 and CH_4.
- Due to uncertainties in calibration of the LGR instrument, NH_3 data from AiRRmonia are used for modelling and for comparison with DPAS-MANDE experiment.
- 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).
- Changes in ammonia concentrations across the treebelt at Poultry 3 using three different methods (ALPHA®, AiRRmonia and DPAS) were comparable when averaged over the four sampling periods. A range of 41 - 45% decrease in NH_3 concentrations across the treebelt was observed for these three methods compared to the SCAIL model value of 29% which assumes no trees are present, further support for the hypothesis of NH_3 mitigation by treebelts.
- 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.
- Ammonia concentrations from a combined 30˚/60˚ arc that focussed on the ranging area and excluded the shed, reduced by about 65% between the “Before Trees” and “After Trees” positions.
- The greater reduction for the ranging area 30˚/60˚ arc (65%), compared to the shed 30˚ sector (25%), may have occurred because the ranging area emissions

were at ground level, and so were more likely to be intercepted and abated by trees. By contrast, the shed emissions were from its eaves at ~3 m above ground, so that some of the ammonia plume may have passed over the trees and not been abated.

Modelling

- An explicit model which calculates the capture of NH_3 by trees (MODDAS-OpenFoam) was run for each of the farms using the measured local conditions (LAI, height, depth). The percentage capture ranged from 80% (Dairy 2) to 0.1% (Poultry 4). 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% ammonia capture.
- LAI, height and treebelt depth are key determinants for NH_3 capture. As trees grow, they gain height and subsequently increase their canopy and LAI which give rise to higher NH_3 capture. Treebelts planted for ranging livestock are unlikely to capture significant amounts of NH_3 in the first 5 years based on outputs at Poultry 4 (treebelt = planted x years ago).
- 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)..
- Poultry 1 showed for all four periods a positive effect from both sheds (5-24% difference from the model results). Poultry 2 (10-18%) and Dairy 1 (5-23%) showed similar response in all but one period at Dairy 1 which could be due to the wind direction. One transect at Poultry 2 through the treebelt on the south side should an opposite effect where the model showed a larger decrease in concentrations.
- Modelling of very near point sampling sites give much lower concentrations than the measurements as seen at Poultry 4 and Poultry 1 which may be down to increased concentrations in the measurements from downwash and/or the source-receptor distance in the model being too short for the dispersion to have started in the model.

1 Introduction

Ground level NH_3 concentrations generally decline exponentially with distance from sources such as animal housing, with the largest change occurring within the first 150 m (e.g. Fowler et al., 1998, Theobald et al., 2004) (Figure 1). Treebelts close to sources such as livestock buildings can potentially reduce NH_3 concentrations and deposition to nearby sensitive receptors. The processes which contribute to this include:

1) Sheltering between source (e.g. farm buildings) and woodland which potentially reduces NH_3 volatilisation from surfaces by decreasing wind speed.

2) Local recapture of NH_3 by the surfaces of the trees - in particular the leaves. intercepting and capturing NH_3 at or very near its source (e.g. from livestock buildings). Woodland has a high surface area with which the NH_3 gas can interact.

3) The increased surface roughness, compared with low-growing semi-natural vegetation, increases turbulence and mixing of the emissions with background atmosphere enhancing dilution and dispersal of emitted NH_3.

4) Recapture of NH_3 from free-range livestock under trees.

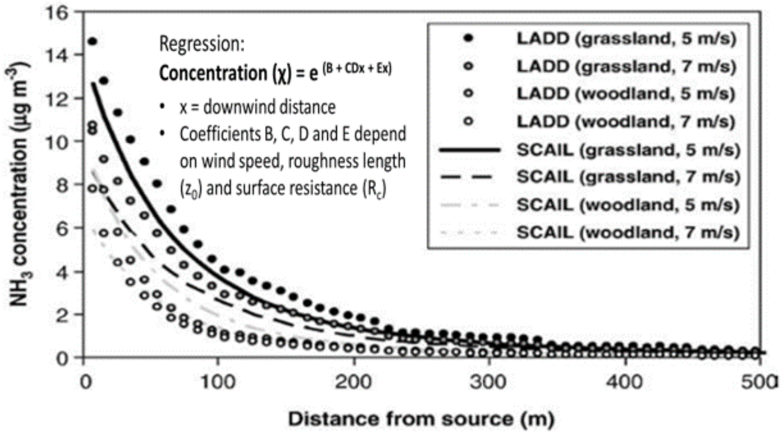


Figure 1: Example concentration profiles from the LADD and SCAIL models for different land cover types and wind speeds. Concentration is at ground level and the distance is from the downwind edge of the source (reproduced from Theobald et al., 2004).

Different approaches to measure and understand the NH_3 plume and concentration reduction downwind from livestock installations with and without trees are studied in this work. One approach is to make an assessment of the NH_3 concentrations that is due to emission from the farm, using passive samplers along a transect downwind of the emissions source to characterise the curve in Figure 1. Ideally there is a stable low concentration “background” NH_3 concentrations, as represented by the mean monitored concentrations at the background sites which ideally should be subtracted from the concentrations along the respective downwind transects. If a perfect wooded and non-wooded transect with identical emissions were found, the difference between the source emissions, plume dispersion and chemical recapture could be quantified. It is understood that a perfect field experiment is rare.

Measurements at high temporal frequency can be used in conjunctions with meteorological measurements to either validate models or drive backward Lagrangian modelling to calculate source strength. With meteorology the high resolution data can disaggregate sources within a landscape in a quantitative way. Innovative directional samplers, sensors and ecological measurements also have potential to support efforts to improve understanding of on-farm emissions and effects.

Emissions from poultry housing are expected to be high throughout the year. Since the concentrations are dominated by the poultry cycle, it is expected that there should be little seasonal pattern in ammonia concentrations around the poultry farm. However, concentrations are also expected to be smaller during periods when sheds are empty and larger concentrations during for example, warm periods when building ventilation would be increased and NH_3 volatilisation is favoured (Riddick et al. 2018, Sutton et al. 2020).

Work Package 2 activities in the ART project were to build further the evidence base for understanding the reduction effect and techniques in the field which are used to qualitatively and quantitatively understand the process. NH_3 concentrations were measured at five case study farms in Cumbria with existing woodland planting in the vicinity of livestock housing. The aim of the study is to provide field measurement data to contribute towards assessing how effective treebelts are at reducing NH_3 concentrations downwind of a variety of agricultural livestock housing and to provide datasets for current and future model verification.

Activities were:

1. Identify case study farms (poultry, dairy) with existing treebelts.
2. Design and establish low temporal, multi-location passive sampling monitoring to measure NH_3 concentrations over approximately a 5 month time frame across the farm landscape (covering summer-winter, 5 - 10 sampling locations) and to undertake relevant ecological measurements at these locations.
3. Undertake a 1 - 2 month intensive measurement period at a suitable farm (Poultry 3). This involved establishing NH_3 concentration measurements at high temporal resolution, before and after a treebelt, downwind of a poultry housing with co-located meteorology. The purpose of this would be to establish an evidence base for plume dilution across the treebelt and provide data for future model analysis. Additional automatic instruments for continuous measurement of carbon dioxide (CO_2), methane (CH_4) and particulate matter (PM)were made available by the Environment Agency (EA). This allowed demonstration of using CO_2 and CH_4 as non-reactive tracer methods for NH_3, to separate the dispersion and vegetation capture aspects leading to reduction in downwind surface concentration of NH_3.
4. SCAIL model assessment of case study farms: Quantify the capture of NH_3 by trees using measurements made within this project and SCAIL model simulations coupled directly with the air dispersion model AERMOD.
5. Case study analysis: Write up data and identify any common conclusions across the measurement sets differences due to different age and depth of treebelts (and where they are in relation to farm sources) and contrasting size and orientation of livestock housing to the prevailing wind.
6. Summarise the study and make recommendations for future analysis of data.

In support of the chemical measurements, ecosystem measurements were undertaken. These provided tree growth, tree canopy morphological parameters and nutrient uptake data to test how effective tree treebelts and woodlands are at capturing NH_3 emissions on poultry and dairy farms in Cumbria. The data was collected to help develop and test models for NH_3 capture by trees and improve data and information for farmers on planting tree treebelt/woodland for NH_3 capture and other benefits.

A Directional Passive Atmospheric Sampler (DPAS®, EA/Lancaster University designed) using UKCEH mini annular denuders (MANDEs) was deployed at the Poultry 3 farm, before and after the treebelt as part of its design and performance testing. This was a first opportunity to deploy the DPAS/MANDE system alongside automatic ammonia monitors at an intensive agriculture site.

All data once archived will be available for providing more information on the effects of NH_3 on the trees and lichens in the woodlands and effectiveness of trees in capturing NH_3.

2 Methodology

2.1 Case study farms

Five case study farms were selected from a list of candidate poultry and dairy farms identified in Cumbria (Table 1). These have different age and depth of planted treebelts, or existing woodland, and have contrasting size and orientation of livestock housing to the prevailing wind. The prevailing wind in the UK is mostly from the SW. Therefore the treebelts are usually planted to the NE of the buildings. Enhanced NH_3 concentrations close to livestock units will occur in an area within 0.5 km of source, with concentrations reaching background at a distance of about 1 km from source (e.g. Pitcairn et al., 1998, Theobald et al., 2009). The focus is on intercepting and capturing NH_3 within the high concentrations zone. Planting is therefore < 35 m from the housings to maximise the capacity of the treebelt for capture.

The criteria used to select suitable case study farms in Cumbria were:

1. Existing woodland planting,
2. Tree treebelts are within 200m downwind of the source.
3. At least 1-2 dairy farms to be included in the study with downwind trees
4. Poultry farms with free-range poultry (laying hens) in and trees downwind of the source.

Each farm provided background information on the farm enterprises and farmers, sources of NH_3 on the farm, description of tree planting design (spacing, species and planting plan). Details of the farm operations during the time of the NH_3/particulates monitoring were collected, including number of birds, age, times housed, clearing out of the sheds, and slurry and fertiliser applications (Arkle 2020). Details of all the farms considered and the decision framework are provided in the file embedded in Appendix A.

Table 1: Summary information on the five case study farms

Type	Name / NH_3 source	Details
Dairy + Poultry	Dairy 1 Mixed and complex sources	• 12 yr woodland and ancient woodland nearby (300m NE of farm). • Open *vs* wooded transects • Lichen survey possible.
Dairy	Dairy 2 350 dairy cows inc. followers. Housed year round (some dry cows +heifers will go out)	• Mature woodland close by sheds ~70m • Woodland 250 m deep (with some open areas) • Ancient replanted woodland, close to River Eden SAC. • Open *vs* wooded transects • Lichen survey possible.
Poultry 1	Poultry 1 26k birds	• Good depth of tree-belt (100 m), 11yrs • Right orientation to prevailing wind • 3 sheds (26k birds) • 1 of 3 sheds is roof ventilated (12k birds)
Poultry 2	Poultry 2 12k birds	• Open vs wooded transects • Single shed • Natural ventilation

Poultry 3/4	Poultry 4 32k birds Poultry 3 6k birds	• Contrasting tree-belt depths: poultry 4 =100m, poultry 3 = 25 m • Contrasting tree ages: poultry 4 = 7yrs, poultry 3 = 12 yrs • Contrasting orientation of sheds: poultry 4 = perpendicular, poultry 3 = parallel • Natural ventilation

2.2 Ammonia monitoring at five farms

NH_3 monitoring sites at the five study farms were established in early August 2020 by personnel from UKCEH, Lakes Free range and Cumbrian Farm Environment Partnership. Atmospheric NH_3 concentrations were monitored using the UKCEH ALPHA® (**A**dapted **L**ow-cost **P**assive **H**igh **A**bsorption) samplers (Tang et al., 2001). Protocols developed for the UK NAMN (Tang et al. 2003) and working instructions are in place to cover ALPHA® sampler deployment covering: sample preparation, sample dispatch, sample handling at monitoring locations, sample receipt, sample analysis at UKCEH Edinburgh and data quality control. The UKCEH ALPHA® passive sampler methodology and protocol are summarised in Appendix 6.1.

Ten monitoring locations were established at each farm to provide measurements of atmospheric NH_3 concentrations that will be combined with on-site meteorology to assess the concentration variability at each location and reduction of NH_3 by the treebelt (in combination with modelling). The spatial assessment of concentrations at each of the farms consisted of:

- **Housing plume**: local transects downwind of emission source. Minimum = 3 monitoring points. At each farm, sites were established along a transect through the tree treebelt in front, centre and behind, where possible. Since the prevailing wind direction is predominantly from the southwest, the monitoring sites were mostly positioned at locations in a northeast transect downwind of the farms. Transects were also set up along other wind directions, depending on the location of the tree treebelt to the NH_3 source. Monitoring in front and behind tree treebelts, to facilitate current and future model validation.

- **Background site** at each test location to provide "representative" background for area, to compare with regional background for grid square from APIS website.

- **Confirm or identify nearby NH_3** emissions sources (farm buildings, fields) that may interfere in NH_3 measurements. Monitoring points were located, where required, to identify contribution from these sources.

- **Paired monitoring** of location behind a tree treebelt with a location in an open area (e.g. gap in trees) at roughly the same distance from source, where possible.

- If there was a **sensitive habitat** downwind of source: Edge of reserve nearest source exposed to largest NH_3 concentrations and NH_3-N deposition, with centre of reserve less exposed to NH_3 concentrations and NH_3-N deposition.

The sites closest to the animal houses were measured and located using a 50 m tape measure and the exact distances of the more distant sites were determined on google maps from GPS coordinates. The 10 passive sampling sites were established with an in-person visit by UKCEH staff and the location of the samplers agreed both for the purposes of measurement and for practicality from the perspective of the farmers.

2.3 Intensive measurements at one farm

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 (Figure 2). Table 2 and Table 3 summarise the instruments and measurements that were deployed at intensive site 1 and site 2, respectively. Figure 4 shows annotated photos of each of the intensive measurement set ups. Table 4 and

Table 5 summarise the sampling air manifold which the continuous gas analysers were connected to. These were set up following the US EPA reactive gas sampling guidelines such that the residence time of the air between the ambient environment and the analyser is <5 s. All instruments were calibrated at least twice through the campaign and details are discussed in the Section 3 alongside the results. Data was collected at the standard resolution of the instruments (e.g. AiRRmonia 1 minute, CO_2, CH_4 1 s.) and averaged to the same time resolution for analysis.

Three Directional Passive Air Samplers (DPASs) were deployed at the intensive measurement farm to measure reductions in airborne ammonia along downwind transects through poultry activities and a 25m tree belt. Each DPAS had an inner carousel that was divided into 12 30° channels, and each channel was fitted with a Mini Annular Denuder (MANDE) to accumulate ammonia fluxes from that 30° sector (Figure 3), and were aligned with the orifice (air inlet) facing the air flow through the DPAS. Fluxes were accumulated over 2-week periods and combined with data on wind speed and direction, in order to evaluate the period-average flux and concentration of ammonia from each sector. Four 2-week periods were monitored between 17 September & 11 November 2020. DPASs were deployed near a shed containing 6000 organic birds which had an adjacent ranging area and the 25m tree belt (Figure 2 right). They were deployed at 3 positions near the shed: (DPAS 1) ~50m upwind of the shed (with respect to the prevailing wind), (DPAS 2) ~25m downwind of the shed but before trees, and (DPAS 3) at a further ~25m downwind after trees. A fuller approach for DPAS analysis and approach is given in Appendix 6.3.

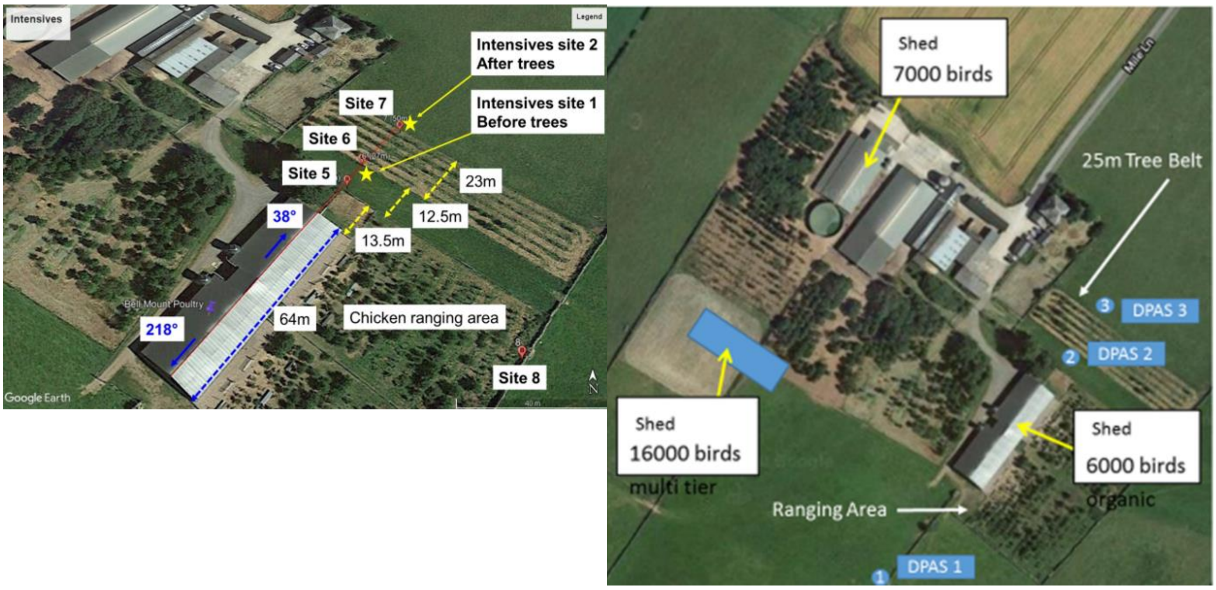


Figure 2: Map of the Poultry 3 Poultry Farm study area, yellow stars showing the locations of the two meteorological and intensive measurement sites; RHS shows the location of the Directional samplers (DPAS)

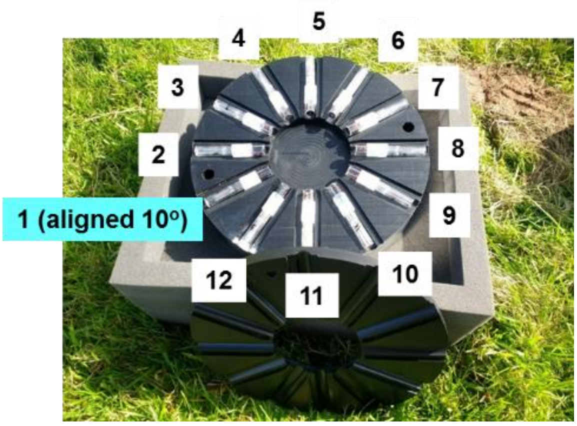


Figure 3: DPAS carousel with MANDE (Mini-ANnular DEnuders) in position, showing orientation and corresponding numbering of sampling position within the DPAS.

Table 2: Measurement equipment deployed at Intensive site 1

Equipment	**What is measured?**
Meteorological station with 3D sonic anemometer & WXT sensor	Wind direction, wind speed, temperature, relative humidity, solar flux, atmospheric turbulence
AiRRmonia online ammonia gas analyser	Continuous NH_3 (data logged at 1 minute resolution and aggregated to 15 minute averages as known response time)
LGR ammonia gas analyser	Continuous NH_3 (data recorded at 1 s resolution, response time not specified as dependant on setup)
CH_4 gas analyser	Continuous CH_4 (data recorded at 1 s resolution, response time not specified as dependant on setup)
CO_2 gas analyser	Continuous CO_2 (data recorded at 1 s resolution, response time not specified as dependant on setup)
DPAS-MANDE	2-weeky NH_3
ALPHA	2-weekly NH_3

Table 3: Measurement equipment deployed at Intensive site 2

Equipment	**What is measured?**
Meteorological station with standard weather sensors	Wind direction, wind speed, temperature, relative humidity
AiRRmonia online ammonia gas analyser	Continuous NH_3 (data logged at 1 minute resolution and aggregated to 15 minute averages as known response time)
LGR Ammonia Analyzer	Continuous NH_3 (data recorded at 1 s resolution, response time not specified as dependant on setup
CH_4 gas analyser	Continuous CH_4 (data recorded at 1 s resolution, response time not specified as dependant on setup
CO_2 gas analyser	Continuous CO_2 (data recorded at 1 s resolution, response time not specified as dependant on setup
DPAS-MANDE	2-weeky NH_3
ALPHA	2-weekly NH_3 (Site 7)
FIDAS PM analyser	PM_1,$PM_{2.5}$, PM_{10} and total suspended particulate matter (TSP

Table 4: Site 1 UKCEH van air sampling manifold set-up

	Dimensions (cm)		Volume (cm^3)	Flow ($l.min^{-1}$)	Residence (s)
	l	d		Max	
Inlet	300	1		-	0.24

Manifold	30	7	1154	19	1.01
AiRRmonia	20	0.5		1	0.02
LGR	50	0.5		0.13	0.39

Table 5: Site 2 EA van air sampling manifold set-up

	Dimensions (cm)		Volume (cm^3)	Flow ($l.min^{-1}$)	Residence (s)
	l	d		Max	
Inlet		1		-	0.24
Manifold	3	0.5	1154	19	1.01
AiRRmonia	20	0.5		1	0.02
LGR	20	0.5		0.13	0.39

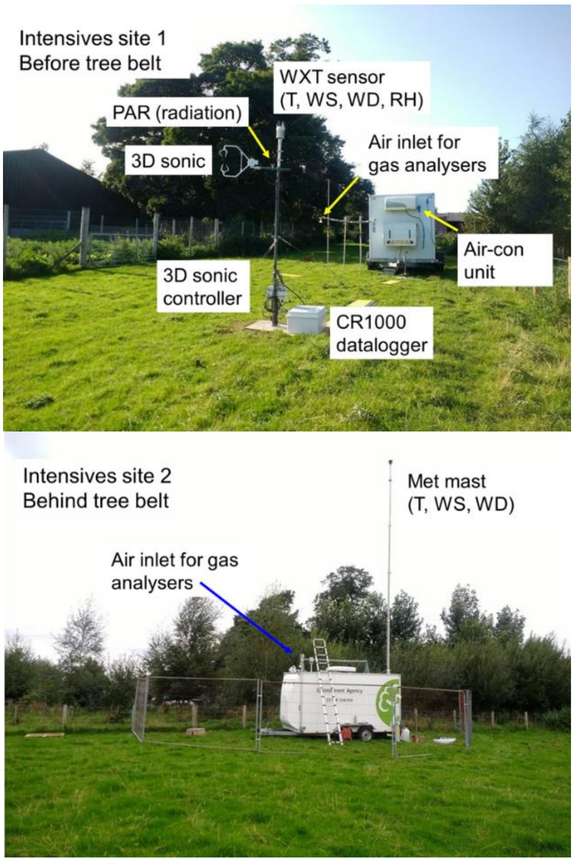


Figure 4 Intensive meteorological and NH_3 measurements: Top image: site 1, between treebelt and poultry shed / ranging area; bottom image: site 2 far side of the treebelt

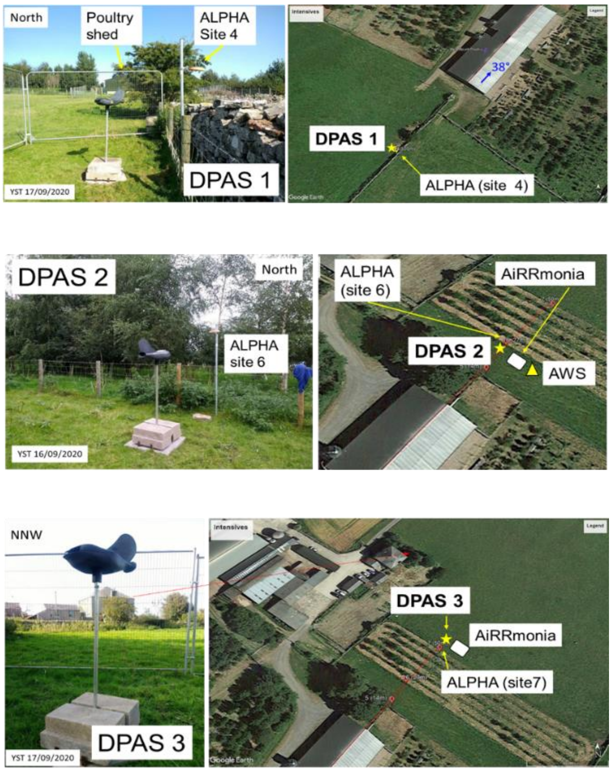


Figure 5 Photos of the DPAS sampler at the three locations. DPAS 1: upwind of poultry housing, DPAS 2: before treebelt (co-located with intensive site 1) and DPAS 3: after treebelt (co-located with intensive site 2).

2.4 Tree growth, leaf morphology and nutrient uptake

2.4.1 Sampling methodology

Five trees of different species at each point along the transects at the farms have been measured for height and diameter at breast height. Canopy leaf samples were also taken. The same five tree species, where possible, were replicated at each point along the transects. The sampling was carried out by Forest Research (FR) Technical Support Unit using extended tree pruners. Canopy photography was also taken from each of the sampled tree. Tree foliage was sampled at the end of September for foliar nutrient levels (C, N, Ca, Mg, K, P and all metals) and leaf morphological measurements (e.g. leaf weights, leaf area, specific leaf area). Samples were taken from each tree and sent by overnight courier to the analytical laboratory of Forest Research at Alice Holt. Upon receipt, samples were visually inspected for signs of disease and insect predation. Specific leaf area was measured before chemical analyses by digital scanning a random selection of 20 leaves per tree and carrying out image analyses using WinFoliar software. Tree leaves were also weighted for biomass (per 100 leaves per tree), carbon and nitrogen analysed by Total Carbon Analyser by Combustion and chemical analyses of Ca, Mg, K, Al, P, Mn and Fe were performed by sulphuric acid digestion and analysed by ICP-OES.

Tree leaf area index (LAI) was calculated by different modelling approaches using input measured data of tree height (m) and diameter (cm) and Specific Leaf Area (m^2/g). Modelled LAI was tested against LAI measured by tree canopy photography using HemiView Software, but this approach also needed the canopy projections for different tree species so the best approaches using diameter/foliage biomass relationships was selected for the final results. Comparison was also made with previously modelled LAI of young trees by 3PgN process-based model. Site specific LAI was calculated using tree LAI and tree density for each farm. Nitrogen canopy uptake was calculated by using the estimated tree canopy foliar biomass and nitrogen concentration.

2.5 Corticolous (bark) lichen surveys

Lichens have been used to monitor UK air pollution since the 1960s (Hawksworth & Rose, 1976) initially for sulphur oxides and oxyacids emitted from fossil fuel burning. The sensitivity of many species to sulphur oxides was soon found to extend to other air pollutants including fluorides and nitrogen oxides. Today, the main gaseous air pollutants are nitrogen oxides (NO_x) and NH_3 and there has been much research upon their effects on lichens worldwide (Mitchell et al., 2005; Yemets et al., 2014; Will-Wolf et al., 2015; Türk, 2018).

In this work, corticolous/bark lichen surveys were carried out at Dairy 1 and Dairy 2 farms. The surveys reported here are part of a wider investigation under the Ammonia Reduction from Trees project into the effects of trees on dispersal of gaseous nitrogen compounds released as a result of dairy cattle and egg-laying poultry farming in rural Cumbria. Cryptogamic epiphytes receive their nutrition directly from the atmosphere and many are sensitive to elevated levels of gaseous and particulate compounds of nitrogen resulting from agricultural and industrial activities (Wolseley et al., 2006). Several tools involving lichens have been developed to link the presence/absence of certain target species to specified levels of atmospheric pollutants. The aim of this study is to survey trees for target lichen species close to sampling sites for atmospheric nitrogen compounds (NH_3) and equate the results with estimated nitrogen deposition values. These estimates can then be compared with the known values of NH_3 concentration taken from the atmospheric sampling points.

A standard methodology was used for the collection and analysis of lichen data (Wolseley et al., 2012) as described in the Field Studies Council. The Field Manual can be downloaded at: www.apis.ac.uk/nitrogen-lichen-field-manual. This method uses information obtained from the branches of birch (Betula spp.) and oak (Quercus spp.). The presence or absence of target species (Table 6) was recorded from five branches at distances of 0-50, 50-100 and 100-150 cm from the branch tips. The data were then tabulated and two indices calculated, LIS (Lichen Indicator Scores) and NAQI (Nitrogen Air Quality Index) using the relevant regression equation. Sites that are designated as clean have an NAQI between 0 and 0.5, at risk NAQI > 0.5-0.85, N polluted NAQI 0.86-1.25, very N polluted NAQI > 1.25.

Background oxidized nitrogen levels at the site were accessed using the APIS location tool; www.apis.ac.uk/search-by-location permitting an estimate of atmospheric NH_3 concentration through the relationship: $NAQI = 2[NH_3] + [NO_2]$ in μmol m^{-3}. The lichen survey was conducted at sampling points along transects up to 450m from the farm buildings, as shown in the photos below, at two study farms: Dairy 1 farm (dairy and free-range hens in a tree treebelt) and Dairy 2 farm (dairy farm with mature woodland).

*Table 6: List of lichens used in the assessment. Those species encountered during the NAQI surveys are indicated by *. Nitrogen-tolerant species are shown in bold.*

Species	Dairy 1 Farm	Dairy 2 Farm
Amandinea punctata		
Arthonia radiata	*	*
Bryoria fuscescens		
Candelariella reflexa	*	*
Evernia prunastri		
Graphis spp.		
Hypogymia physodes		*
Lecidella elaeochroma	*	*
Ochrolechia androgyna		
Parmelia spp.	*	*
Physcia adscendens/tenella	*	*
Pseudevernia furfuracea		
Punctelia subrudecta		*
Sphaerophorus globosus		
Usnea spp.		
Xanthoria parietina	*	*
X. polycarpa/ucrainica	*	

2.6 Modelling Farms Case Studies

Modelling to identify any effect of treebelts on the NH_3 concentrations from the farm sources was done with two different models: 1) SCAIL Agriculture (Simple Calculation of Atmospheric Impact Limits and 2) MODDAS-OpenFoam (MODDAS-OF) treebelt model

2.6.1 SCAIL Agriculture

The SCAIL Agriculture (Simple Calculation of Atmospheric Impact Limits) model was ran for each farm based on known animal numbers to obtain NH_3 concentration values at each of the measured monitoring stations. SCAIL is an online screening tool for assessing the impact from agricultural and combustion sources on semi-natural areas like SSSIs and SACs. It uses the air dispersion model AERMOD (US EPA, 2005) to drive the modelling. In SCAIL these are known as the 'receptor' points which are used for modelling sensitive habitats around an NH_3 source. In this work we used the measurement locations (ALPHA sampling poles) as the receptor points of known distance from the farms (see Section 3 for aerial images of transects and measurement locations)

The main work was to identify the relevant periods in the study period with the wind direction from upwind of the housing, which would carry directly the NH_3 plume from the housing unit and through/over the treebelt. These parts of the measurement periods were modelled with these conditions and compared with the measured values. Since the model does not take into account trees in the landscape, i.e. it models a flat terrain, concentrations modelled and measured before and after the treebelts can be compared. Differences should provide an estimate of how much NH_3 the trees are dispersing or capturing the ammonia emitted from the housing.

In the North West UK, there is a predominating south westerly air flow which would pass through the treebelt to the north east. Air dispersion modelling requires meteorology to drive the atmospheric processes and determine pollutant concentration receptor points. The key parameters for the AERMOD model within SCAIL are wind direction, wind speed, temperature and relative humidity – with wind direction and wind speed the two key components.

Modelled data was used for all sites. Specifically the UK atmospheric high resolution data (2 x 2 km grid resolution) from the UK Met Office operational NWP (Numerical Weather Prediction) Unified Model (UM). The dataset was used to extract hourly data meteorology statistics for each of the 6 farms for the measuring period July to December 2020. For Poultry 3 farm (and Poultry 4) we also had the meteorological data from the 8 week intensive measurement period in September and October 2020. Figure 6 summarises the wind roses of for each period at each farm site. Table 7 shows the modelling parameters for each farm which also provides the number of animals for each housing unit and the relevant emission factors for the type of housing system applied.

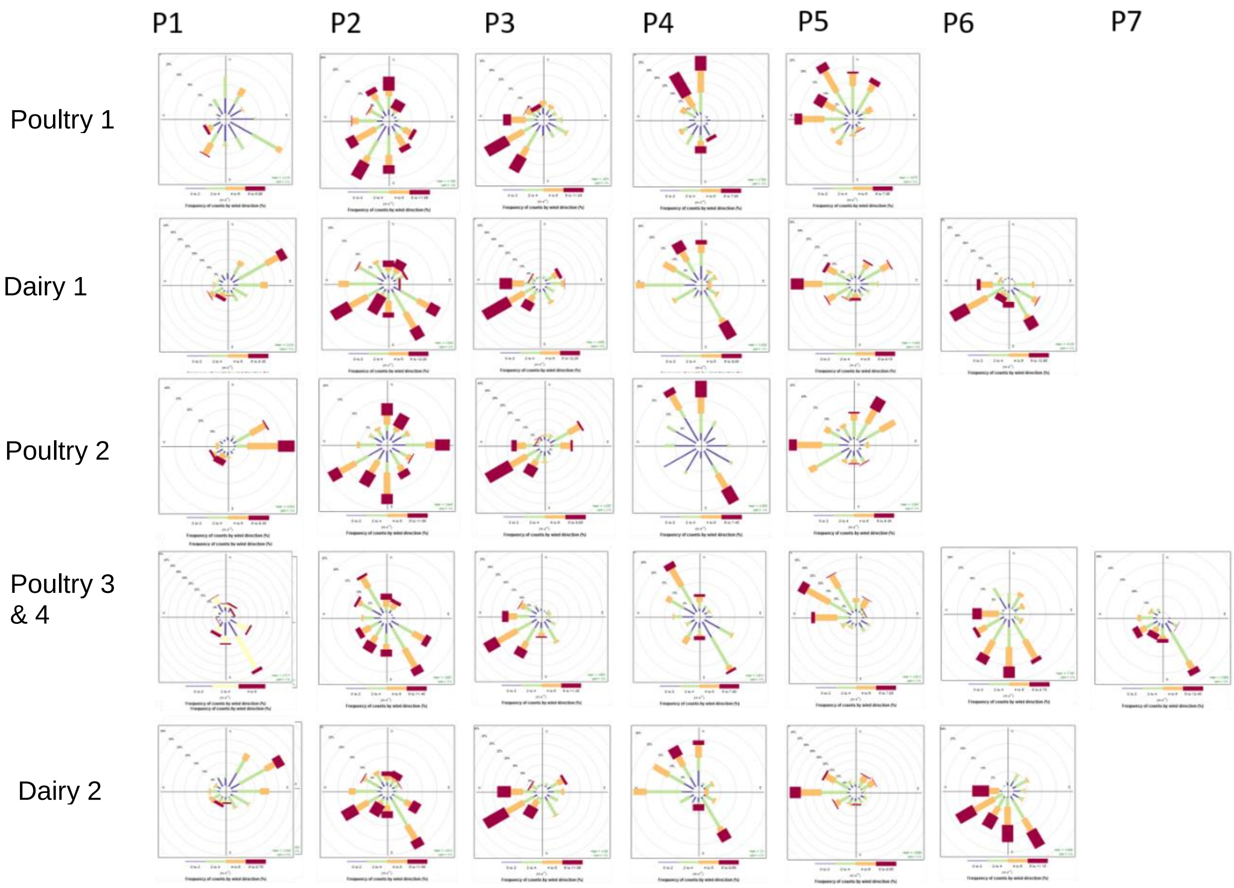


Figure 6: Wind roses across each farm for the months of August to November from the UK Met Office operational NWP (2 x 2 km resolution). Each Period is roughly 2-weekly periods apart from Period 4 which is 5 days. Wind roses reflect the periods when measurement data is available.

Table 7: Input parameters for the SCAIL Agriculture runs across the case study farms

Source Parameters for SCAIL	Housing Type	Housing Height	Animal Type	Animal No.	Emission Factor kg NH_3 animal place^{-1} year^{-1}	Emissions NH_3 t/a
Poultry 1 Shed A (fans)	Fan ventilation Perchery with deep litter	5	Barn free range layers	12000	0.29	3480
Poultry 1 Sheds B	Side ventilation Perchery with deep litter	3.6	Barn free range layers	14000	0.29	4060
Poultry 2	Side ventilation Perchery with deep litter	3.6	Barn free range layers	12000	0.29	3480
Dairy 1	Side ventilation Slurry based cubicle housing	4	Dairy	400	0.071	10366
Dairy 1	Side ventilation Perchery with deep litter	3.6	Barn free range layers	16000	0.29	4640
Dairy 2	Side ventilation Slurry based cubicle housing	4	Dairy	300	0.071	7774
Poultry 4	Side ventilation Perchery with deep litter	3.6	Barn free range layers	32000	0.29	9280
Poultry 3	Side ventilation Perchery with deep litter	3.6	Barn free range layers	6000	0.29	1740

2.6.2 MODDAS-OF treebelt model

In this study we evaluated different the treebelts around the 6 farms using the MODDAS-OpenFoam (MODDAS-OF) model to quantify the capture of NH_3 within the canopy. MODDAS-OF is a flexible two-dimensional (along wind and vertical) model that can be used to examine the NH_3 abatement potential of treebelt structures in the landscape. MODDAS is a Lagrangian stochastic model for gaseous dispersion, coupled with a multi-layer exchange model including a stomatal compensation point (Loubet et al., 2006). OpenFoam is an Eulerian (k-ε) turbulence and fluids dynamics model designed for transfer within the planetary boundary layer as well as within a plant canopy.

The MODDAS-OF model allows the modification of parameters such as downwind canopy length, leaf area index (LAI) and leaf area density (LAD) to be varied, and thereby providing a tool to estimate the NH_3 capture through a treebelt canopy of any depth, height and density. The model scenario setup is based around a woodland schema as shown in Figure 7, where different blocks of woodland or canopy (c) are formed by varying the height of canopy (hc), the length of canopy (xc), the leaf area density profile (LAD(z)), the Leaf Area Index (LAI) (not shown in the figure), the source strength (Qs) and the source length (Xs).

By using the woodland schema, different heights and lengths of woodland blocks of differing LAIs and LAD structures were configured to examine the optimal combination of parameters to maximise NH_3 recapture in the model run. MODDAS-OpenFoam is run for real life conditions at the farm based on Forest Research data on LAI and height, and farm data to quantify the emission strength

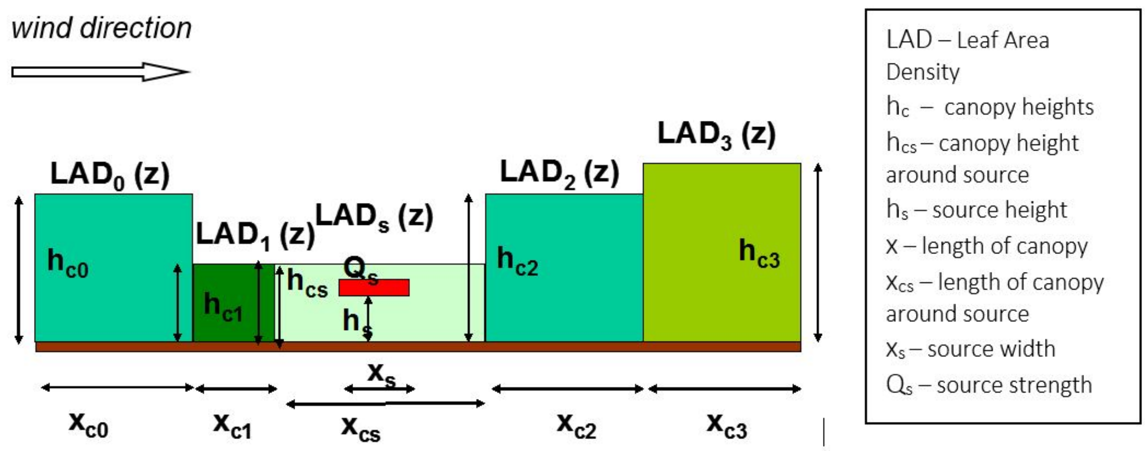


Figure 7 General model scheme of a main canopy and backstop tree treebelt and source geometry that was tested in the scenarios. There is no limit to the different canopy structures that can be added to the model. The red box represents the source with a specified height (h_s) and downwind length (x_s). The wind is modelled to come from one direction.

3 Results and Discussion

3.1 Farm case studies

The NH_3 monitoring work at each farm provided 2-week time-integrated average NH_3 concentrations August-November 2020 (± a few days depending site visit logistics). Ten measurement periods were originally planned for each farm between August and December 2020. Due to site access issues during the avian influenza outbreak in October 2020, October/November samples were not collected until March 2021. Samples exposed for >3 months were not analysed, due to saturation. The measurement periods are summarised in Table 8.

At each farm, the purpose of the background site (site 10) was to provide an indicative "background" NH_3 concentration for the landscape, so that an assessment of the contributions from the farm can be made, over and above the local background. It is difficult to define a "representative background", because atmospheric NH_3 concentrations are spatially very variable due to the large number and type of NH_3 emissions from ground level sources across the landscape. Monitoring at a location upwind of the farm or at a sufficient distance (>150 m) from sources should provide the best indication of the local NH_3 background, provided that the site is not subject to other emission sources close by, and is at a sufficient distance away not to be affected by emissions from the farm.

Table 8: Summary of NH_3 measurement periods made at each case study farm.

Farm	# periods	Measurement Period (P)
Poultry 1	5	**06/08/2020 – 19/10/2020** P6: collected in March – not analysed, long exposure. P7 – P10: samples not used
Dairy 1	7 (8*)	**05/08/2020 – 11/11/2020** *P8: returned 29/03/21 and analysed, but no sample information – no data. P9: collected in March – not analysed, long exposure. P10: samples not used
Poultry 2	5	**04/08/2020 – 15/10/2020** P6: collected in March – not analysed, long exposure. P6 – P10: samples not used
Dairy 2	7 (8*)	**05/08/2020 – 11/11/2020** *P8: returned 29/03/21 and analysed, but no sample information – no data. P9: collected in March – not analysed, long exposure. P10: samples not used
Poultry 3 / Poultry 4	7	**06/08/2020 – 11/11/2020** P8: collected in March – not analysed, long exposure. P9 – P10: samples not used

3.1.1 Dairy 1 (mixed Dairy and Poultry)

Dairy 1 is a large mixed dairy and poultry farm, with a large open slurry pit at the top end (NE) of the farm and a single large poultry shed south of the slurry pit. An ancient woodland is located 300m NE of farm. Tree treebelts (12 years old) were planted around the farm, on the east and southern side. Existing hedgerows and established woodlands shelters the entire site on the north side. This farm is a complex scenario, with a large number of different NH_3 sources that include: dairy buildings, poultry shed and slurry stores. An open and a wooded NH_3 transect were monitored, together with tree growth, leaf morphology and nutrient uptake, and a lichen survey was conducted (Figure 8).

Ammonia monitoring

NH_3 was measured for 6 periods (Figure 8, Table 9). NH_3 concentrations were highest at site 3 (mean = 156 µg NH_3 m^{-3}) located 5m from the poultry housing (on north side) at the farm. Site 3 is downwind of dairy housing and could be expected to from both other parts of the farm and poultry shed. The concentrations measured at site 3 will also be dependent on frequencies of wind blowing from the farm buildings towards the samplers in both the open and wooded transects.

NH_3 concentrations declined rapidly downwind of the farm, reaching small levels of concentrations at site 5 (170 m NE of slurry lagoon, 250 m NE of poultry shed; mean = 4.7 µg NH_3 m^{-3}). The concentrations at site 5 are similar to site 6 at the end of the transect in a clearing of the woodland downwind (270 m NE of slurry lagoon, 350 m NE of poultry shed; mean = 4.1 µg NH_3 m^{-3}). Site 3 is at the start of the wooded transect (sites 3 - 6). The concentrations declined rapidly across the woodland, with a 12-fold decrease in concentration from a mean of 156 µg NH_3 m^{-3} at site 1 to 12.6 µg NH_3 m^{-3} at site 4. NH_3 concentrations at site 8 (80 m SE of poultry shed, behind tree treebelt, mean = 18 µg NH_3 m^{-3}) was on average 16.6% smaller than at site 9 (80 m SE of poultry shed, in a gap in the treebelt, mean = 21.5 µg NH_3 m^{-3}. The results indicate that the tree treebelt is dispersing and/or capturing NH_3 from the poultry sheds and dairy buildings, as NH_3 concentrations declined more rapidly with distance from the livestock housing across the wooded transect compared with the more open transects.

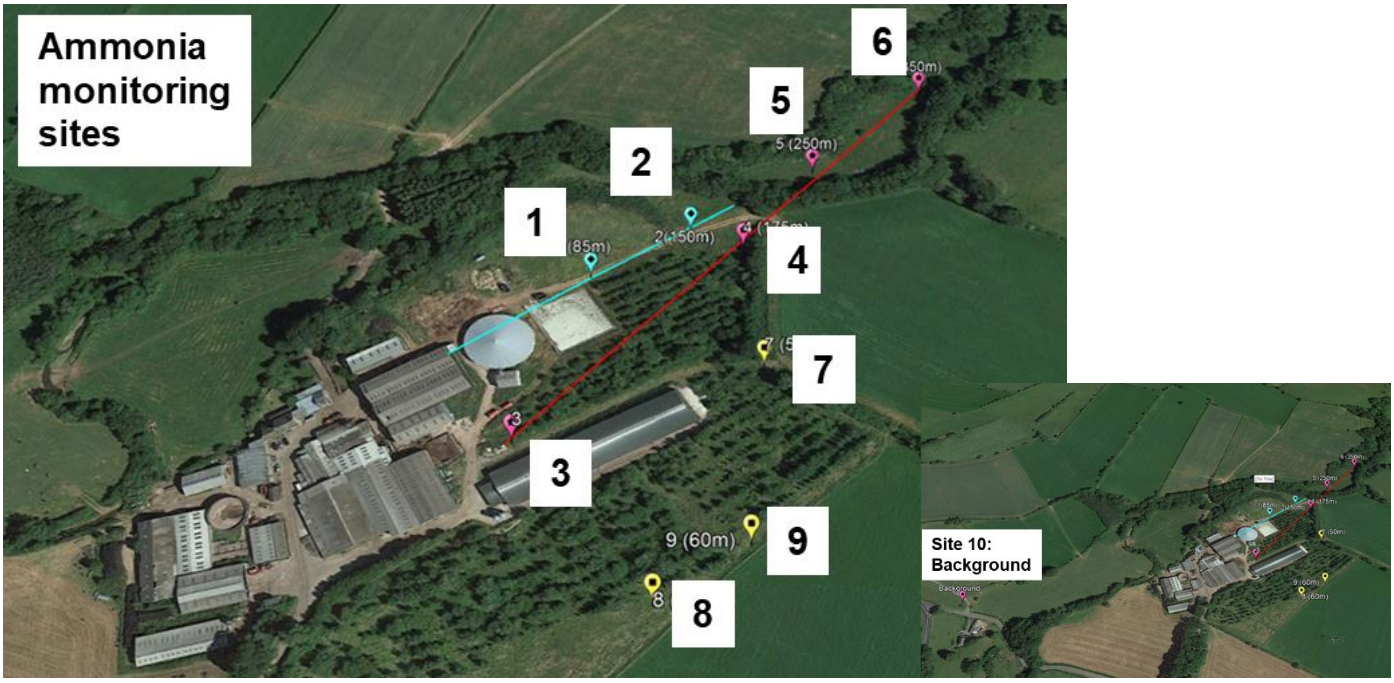


Figure 8 Dairy 1 mixed dairy and poultry farm with locations of NH_3 monitoring points. Background site 10 is in smaller inset image.

Table 9: Monitored NH_3 concentrations with ALPHA® samplers at Dairy 1.

Site ID	Distance from farm (m)	Measured NH_3 Concentrations with (µg NH_3 m^{-3})								
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Mean**	**SD**
		05/08 - 19/08	**19/08 - 03/09**	**03/09 - 24/09**	**24/09 - 30/09**	**30/09 - 19/10**	**19/10 - 30/10**	**30/10 - 11/11**		
1	5 (slurry pit)	30.5	25.8	21.8	15.2	19.4	34.6	25.2	24.6	6.6
2	70	12.1	15.8	13.0	9.9	10.5	18.3	10.7	12.9	3.1
3	5 (poultry shed)	-	170	155	124	122	140	223	156	37.9
4	175	10.3	13.7	14.8	8.5	10.2	18.3	12.10	12.6	3.3
5	250	3.8	6.2	6.3	3.3	2.4	6.8	4.09	4.7	1.7
6	350	3.6	4.3	8.8	2.1	2.0	4.8	3.02	4.1	2.3
7	30	30.8	40.4	74.7	36.3	39.5	59.9	48.7	47.2	15.4
8	60 (in trees)	10.3	22.7	8.8	31.2	16.6	1.8	8.37	14.3	10.0
9	60 (gap in trees)	10.7	26.5	12.2	35.8	22.3	2.5	9.57	17.1	11.6
10	Background	13.8	4.9	7.5	7.1	3.4	1.1	-	6.3	4.4

nd = no data (lost, or rejected due to sampling issues)

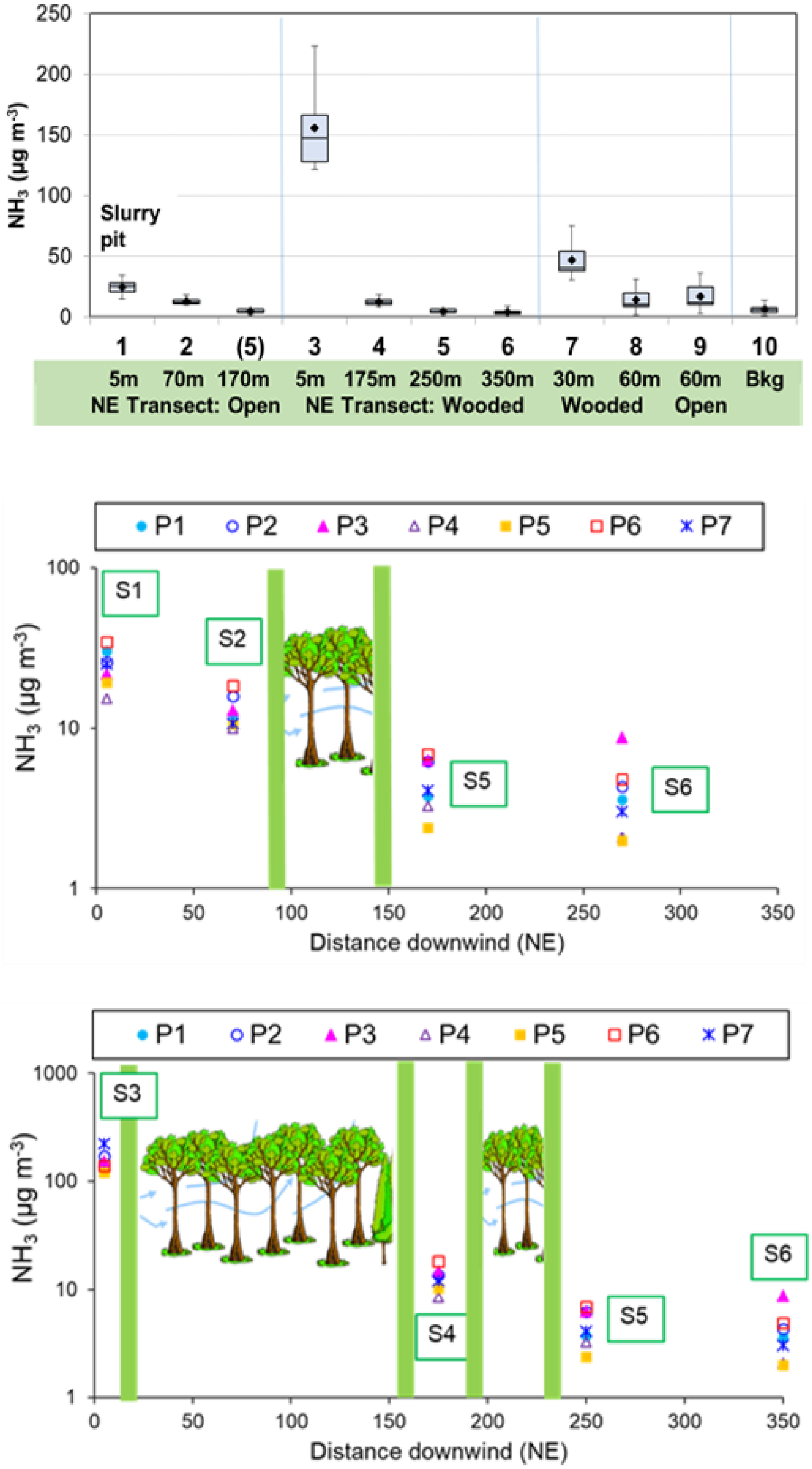


Figure 9 Top: Location of measurement sites, Second: Boxplot comparing concentrations measured at the 10 locations on Dairy 1 farm from 7 measurement periods (05/08/2020 and 11/11/2020). Whiskers are the min and max measured concentrations. Bkg = Background site 10; Third down and Bottom: Data from individual periods

The comparison of changes in NH_3 concentrations between an open transect (sites 1, 2, 5, 6) and a wooded transect (sites 3 - 6) are shown in Figure 10 below.

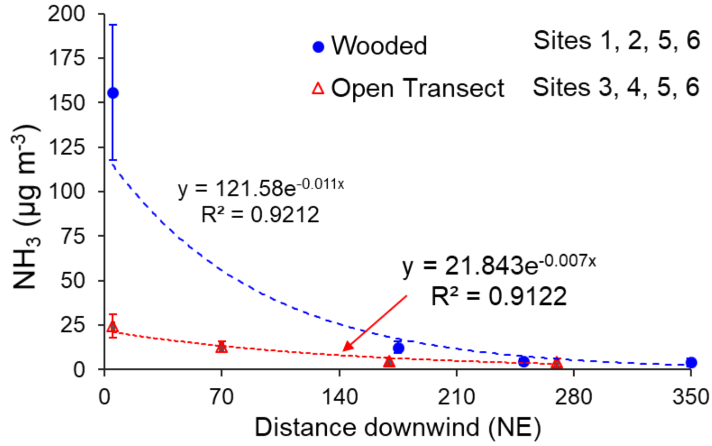


Figure 10: Comparison of changes in NH_3 concentrations between an open transect (sites 1, 2, 5, 6) and a wooded transect (sites 3 - 6) at Dairy 1 mixed dairy and poultry farm. Data shown are the mean ± SD of 7 measurement periods.

Modelling

Due to the large number of sources at Dairy 1 farm, together with the complex nature of their locations it was decided not to run SCAIL at Dairy 1 to determine the effect of treebelts. The other 4 farms represented a ‘cleaner’ source/receptor picture and modelling focussed on those farms.

Tree growth, leaf morphology and nutrient uptake

Tree assessments were made at this site (Figure 11). The results are shown in Table 10 for ten sites. Tree height, diamater, LAI and canopy nitrogen uptake do not exhibit the same trend of declining with distance from Dairy 1 farm which is different to other farms in this study. It is thought that this is due to transect 1 being situated alongside a sluggy lagoon, with the closest point to the lagoon at the 80m point of the transect which shows very high tree growth parameters and nitrrogen canopy uptake. If the anomalous 80m point of the transect is removed from calculations, the tree parameters (diameter, LAI and nitrogen uptake) decline sharply with distance from the farm and levels off after around 50 m. The nitrogen uptake by tree canopies at Dairy 1 farm ranged between 9 and 48 kg N/ha depending on tree species and distance from the farm.

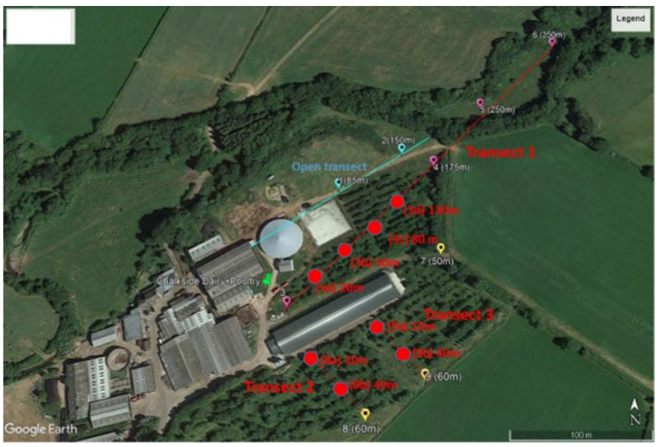


Figure 11: Ecological sampling points. Additional points maked with red were added for tree assessments to increase the number of points along the transects.

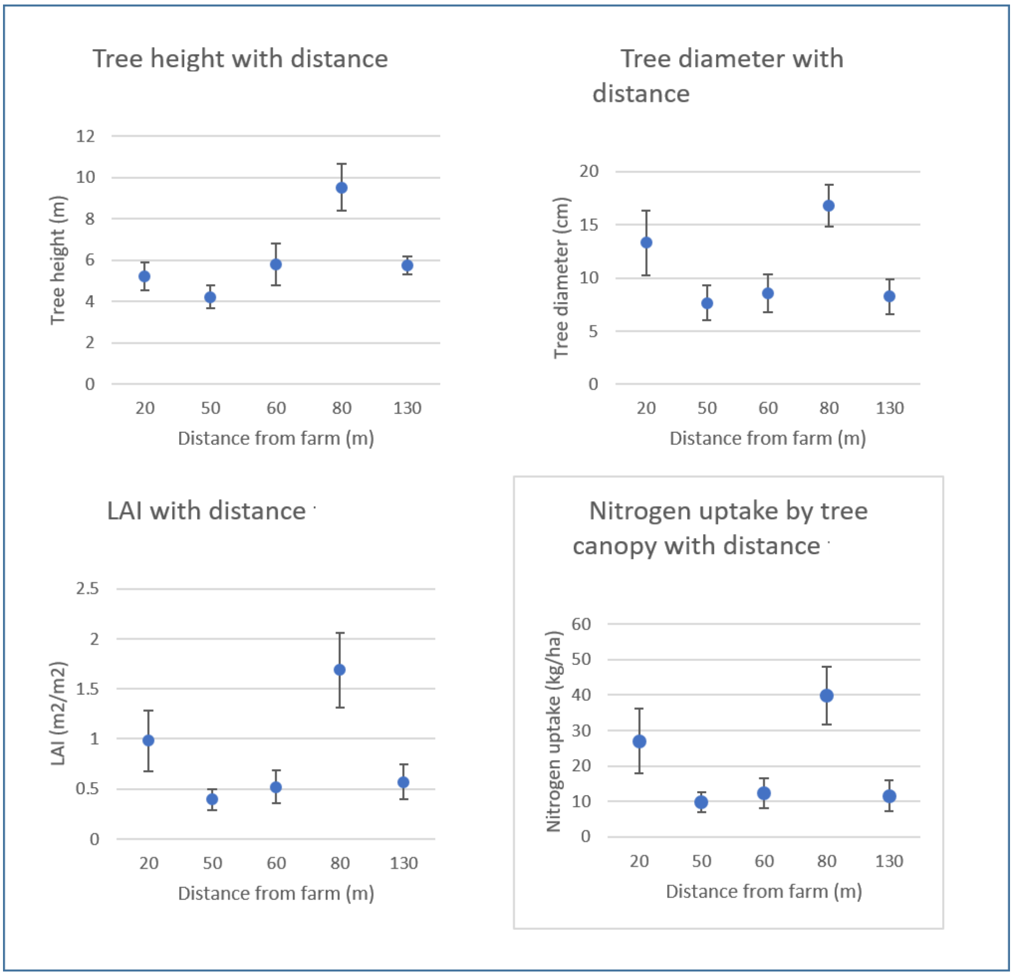


Figure 12 Tree height, diameter, LAI and nitrogen uptake with distance away from Dairy 1 farm. Mean values from 5 trees of different species for each point are presented and vertical bars are standard errors of the mean.

Corticulous (bark) Lichen Survey

Corticulous/bark lichen surveys were undertaken at Dairy 1 farm. The NAQI values are plotted along the transects (sites 1-9) in Figure 13. 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 NOX. 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 *Xanthoria parietina*. The resulting LIS score was low, resulting in an anomalously low 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.

It will be noted that for sites 2, 3 and 5, other tree species had to be used for the study as no oak or birch was available nearby. Despite this the NAQI values for sites 2 and 3 did not differ from those of site 4 (birch) although the NAQI for site 5 (alder) was depressed. Alder is an acid-barked tree differing little in its lichen flora from oak although it usually occurs on wetter soils and tends to have a less diverse flora.

This study was concerned with lichens growing on branches of oak and birch, but a brief examination was also made of the older branches and trunks of these trees (

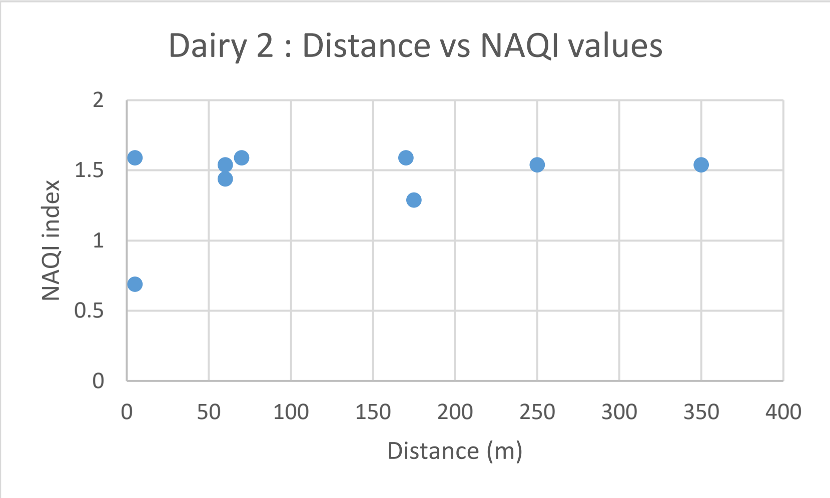


Figure 13*).* Although the results do not influence findings from the NAQI study they are of some interest. In particular, trees at sites 8 and 9 were well covered in non-target lichens. Notable among these were white crusts of the lichen *Lecanora chlarotera*, a common 'twig' species of the lowlands of Cumbria. Here this lichen was locally colonized by another species, *Caloplaca holocarpa*, an unusual feature. The occurrence here of two pyrenolichens, (*Arthopyrenia* spp.) is interesting as these are often associated with unimpacted deciduous woodlands, yet appeared to be forming healthy thalli near the farm. The occurrence of several Physciaceae ties in better with the predicted NAQI scores since all are associated with nutrient-enriched sites such as the birch trees within the poultry enclosure.

Table 10: Lichen survey details with LIS (lichen indicator score) and NAQI (nitrogen air quality index score)

Site No.	LIS	NAQI	$[NH_3]$ µmol m^{-3}	Tree species	Tree position/NGR
1	-0.6	0.69	0.03	B	10m 110º
2	-3.0	1.59	0.40	A	28m 10º
3	-3.0	1.59	0.40	M	33026 45163
4	-3.0	1.59	0.40	B	33128 45270
5	-1.8	1.29	0.23	A	33204 45329
6	-2.8	1.54	0.37	O	33261 45432
7	-2.8	1.54	0.37	O	7m 10º
8	-2.4	1.44	0.31	B	9m 40º
9	-2.8	1.54	0.37	B	10m 350º
10 (control)	-2.0	1.34	0.26	O	32516 45154

Table 11: Additional taxa recorded from the trees at Dairy 1 Farm

Species	**Site**
Arthonia punctiformis	9
Arthopyrenia analepta	9
Arthopyrenia punctiformis	9
Caloplaca holocarpa	8, 9

Lecania cyrtella	8, 9
Lecanora chlarotera	8, 9
Orthotrichum sp.	3
Phaeophyscia orbicularis	3, 8
Physcia aipolia	8, 9
Physconia grisea	3
Rinodina oleae	8

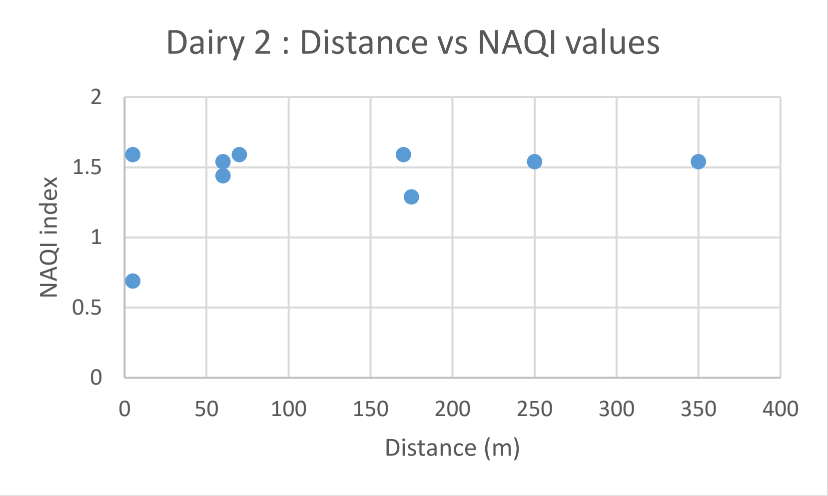


Figure 13: NAQI values along the Dairy 1 Farm transects plotted against distance from nearest source.

3.1.2 Dairy 2

Dairy 2 is a large dairy farm with a slurry store on the south end of the farm building (Table 7). An established replanted mature woodland (mixed broadleaf and conifer) is located to the east and northeast, 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. Cows were grazed in the fields around the farm and in the fields behind the woodland.

Two parallel transects were established downwind of the farm buildings in the prevailing wind direction (Figure 14):

Transect 1 (Sites 1 – 4): This northeast transect was positioned where the southern end of the woodland is in closest proximity (82 m) to the farm buildings. Sites 1 (47 m) and 2 (80 m) are in the open fields (with cattle grazing), before the woodland starts. Site 3 (200m) is in a clearing in the woodland and Site 4 is on the other side of the woodland, 370m along the transect.

Transect 2 (Sites 5 – 9): This parallel transect was deliberately sited to take advantage of the fact that the edge of the woodland here is further away (200 m) from the farm buildings than at Transect 1. Sites 5 – 7 are in the open (47 - 160 m from farm), to compare with Sites 1 and 3 in Transect 1. Site 8 (300 m) is in a clearing in the woodland, to compare with site 3. Site 9 is at the end of the transect on the other side of the woodland (450 m), to compare with site 4 (370m).

A lichen survey was also carried out, as well as local SCAIL modelling.

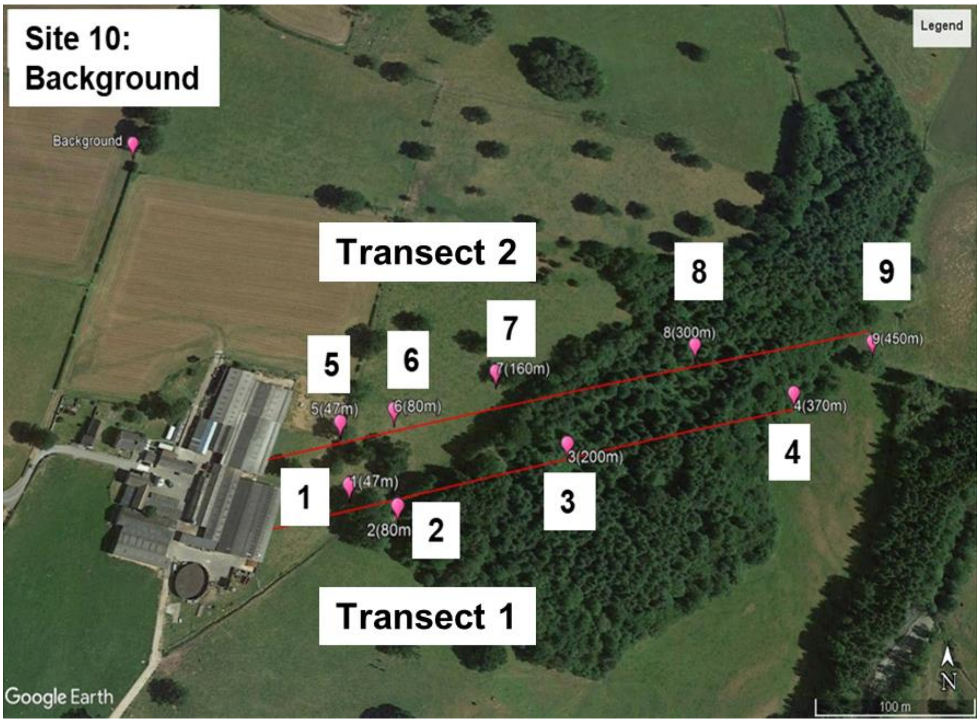


Figure 14: Dairy 2 , showing locations of NH_3 monitoring points along two parallel transects (transect 1 with the 82 m at the start of the 450 m transect in the open (sites 1 – 2) and 2 , with 200 m of the 370 m transect in the open (sites 5 – 7) (prevailing wind direction is assumed to be from the NE). The background site (10) is located to the NNE of farm, between two fields.

Ammonia monitoring

The NH_3 concentrations are summarised in Table 12. NH_3 concentrations closest to the farm building (sites 1 & 2 and sites 5–7) showed the largest variation between measurement periods, likely due to variability in the farm emissions and meteorology between measurement periods. The largest individual sources at Dairy 2 are the intensive livestock units, the slurry store and the fields (grazing and fertilised (with waste or synthetic fertiliser). NH_3 concentrations are generally largest in proximity to livestock buildings, and decline exponentially in concentration with distance away from the source (e.g. Pitcairn et al. 1998, 2002, Ro et al. 2018 and many other studies). NH_3 is also a reactive gas and a significant fraction of the NH_3 emitted is rapidly deposited within 1 km radius of the source (Fowler et al. 1998, Pitcairn et al. 2002). The exponential decline in NH_3 concentrations is therefore deposition and recapture processes, over and above natural dilution and dispersion driven by meteorology.

Table 12: Monitored NH_3 concentrations with ALPHA® samplers at Dairy 2.

Site ID	Info.	Distance from farm (m)	Measured NH_3 Concentrations with (µg NH_3 m^{-3})								
			P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Mean**	**SD**
			05/08 - 18/08	**18/08 - 03/09**	**03/09 - 24/09**	**24/09 - 30/09**	**30/09 - 15/10**	**15/10 - 29/10**	**29/10 - 11/11**		
1	Transect 1	47	10.8	12.3	*Nd*	24.8	20.2	6.9	10.9	**14.3**	6.75

2		80	7.8	8.6	8.9	16.5	9.6	4.6	6.6	**9.6**	4.29
3		200	2.9	2.2	3.2	2.2	4.1	1.9	2.8	**2.8**	0.76
4		370	3.6	2.2	2.1	1.5	2.3	2.2	1.9	**2.2**	0.68
5	Transect 2	47	17.1	22.1	29.5	34.3	36.0	13.2	22.7	**25.0**	8.59
6		80	10.6	12.7	18.3	20.0	25.1	8.4	13.6	**15.5**	5.88
7		160	6.7	5.8	11.7	7.9	12.6	5.6	8.4	**8.4**	2.77
8		300	2.6	1.3	2.3	1.3	1.6	1.4	1.9	**1.8**	0.52
9		450	4.3	2.5	2.4	2.4	3.4	2.3	2.3	**2.8**	0.78
10	Background		17.1	22.1	29.5	34.3	36.0	13.2	22.7	**25.0**	8.59

nd = no data (lost, or rejected due to sampling issues)

A direct comparison between the two transects at Dairy 2 is complicated by the presence of grazing emissions in the fields between the farm and the edge of the woodland. The transects are therefore not from a single point source such as from a single or a set of buildings. Rather, the profile of the transects (sites 1 & 2, and sites 5 – 7) are influenced by local emissions along its length before entering the woodland.

However, it is possible to make both qualitative and some quantitative observations from the dataset. From Table 12 it can be seen that NH_3 concentrations were highest at the sampling points nearest the farm buildings. 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. 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.

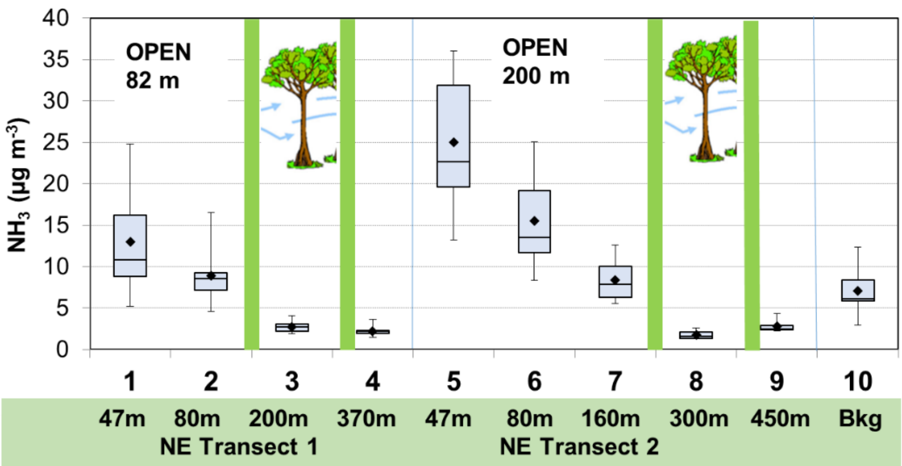


Figure 15: Boxplot comparing NH_3 concentrations measured at each location at Dairy 2 from 7 measurement periods (05/08/2020 – 11/11/2020). Whiskers are the min and max of measured concentrations. Bkg = Background site 10.

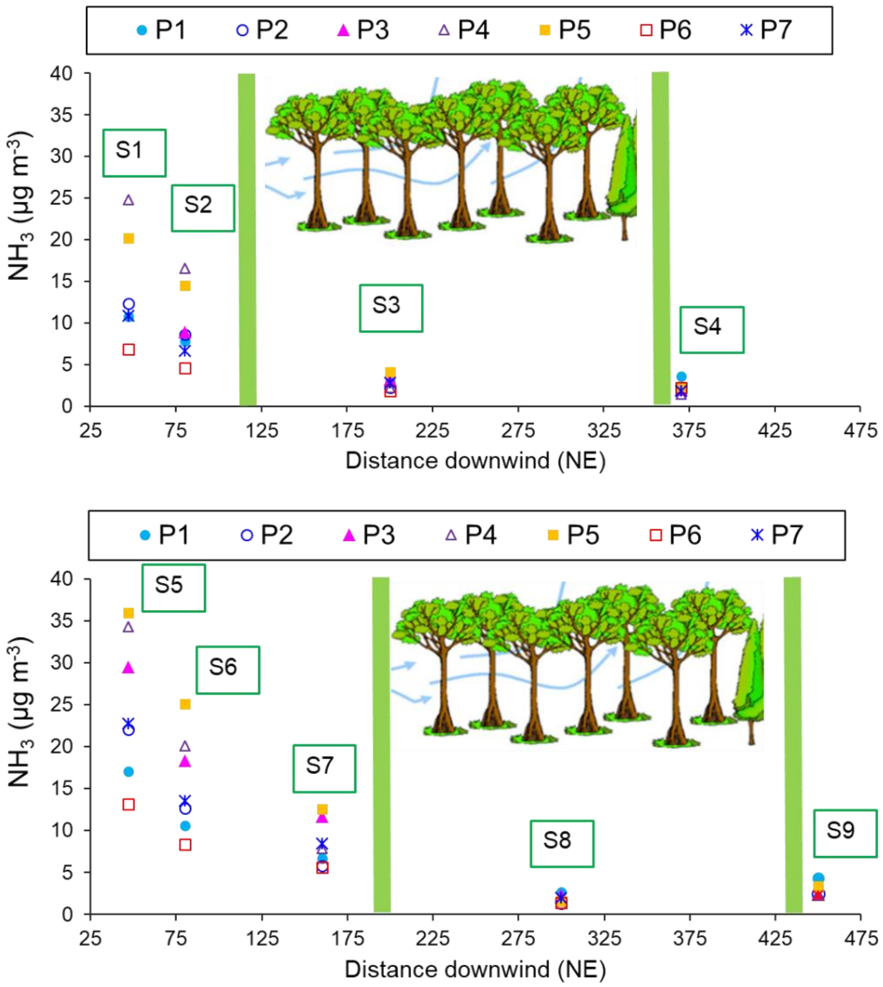


Figure 16: Changes in NH_3 concentrations between (TOP) Transect 1 (sites 1 - 4) and (BOTTOM) Transect 2 (sites –5 - 9) at Dairy 2, showing data from individual periods.

One important observation is that very high background site concentrations were observed (site 10, mean = 7.1 µg NH_3 m^{-3}) suggesting local influence from grazing, (cattle were observed congregating close by) and seasonal manure / slurry spreading. One open question is whether the background site is a representative background or a local anomaly. Given the intensity of the farming activity, it is likely the former of these.

The smaller NH_3 concentrations in the centre and on the far side of the woodland, indicates that the established woodland disperse and/or capture NH_3 from the dairy farm and grazing emissions from the fields. The decrease in NH_3 concentrations between site 2 in the open (mean = 8.9 µg NH_3 m^{-3}, n = 6) and site 3 in the woodland (mean = 2.8 µg NH_3 m^{-3} ,n = 6) is 70 %. This compares with a decrease of 78 % between site 7 in the open (mean = 8.4 µg NH_3 m^{-3}, n = 6) and site 8 in the woodland (mean = 1.7 µg NH_3 m^{-3}) (Table 12).

In Figure 17, an exponential function is fitted to the open sites from each of the 2 transects: sites 1 – 2 from transect 1 and sites 5 – 7 from transect 2. Extrapolation of the fitted curves showed that the mean concentrations from site 8 (300m) in transect 2 is below the line, which suggests potential capture of NH_3 by the trees. Site 3 (transect

1) on the other hand did not deviate from the extrapolated curve, with no evidence for additional reduction in concentrations due to deposition to the trees. There are however only 2 open monitoring points in transect 1, which makes fitting the exponential curve highly dependent on Site 2. Since site 2 is sheltered from behind by a mature tree, this may also have contributed to smaller concentrations than if there were no trees. The data presented here are used to compare with modelled concentrations (see section on modelling), to estimate reduction of NH_3 concentrations by the woodland.

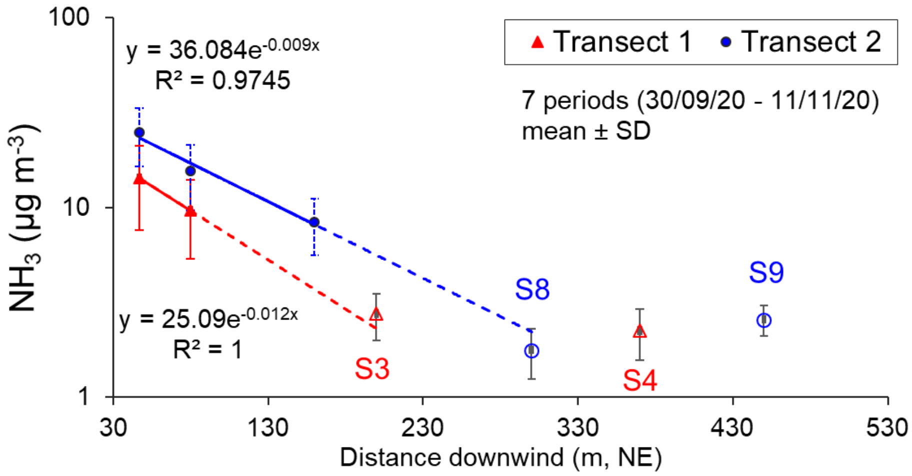


Figure 17 Mean Profile in NH_3 concentrations from transect 1 (exponential curve fitted to open sites 1 – 2 at start of transect and extrapolated to site 3) and transect 2 (exponential curve fitted to open sites 5 – 7 at start of transect and extrapolated to site 8) at Dairy 2.

For Transect 2, an exponential function was fitted between the first three sampling points in the open (Sites 5 – 7: 47m – 160m) in each of the measurement period and extrapolated to provide estimated NH_3 concentrations at 200m for comparison with Site 3 in Transect 1 (200m, inside woodland). 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 18 compares the NH_3 concentrations (and % relative change) between paired sites in the parallel transects.

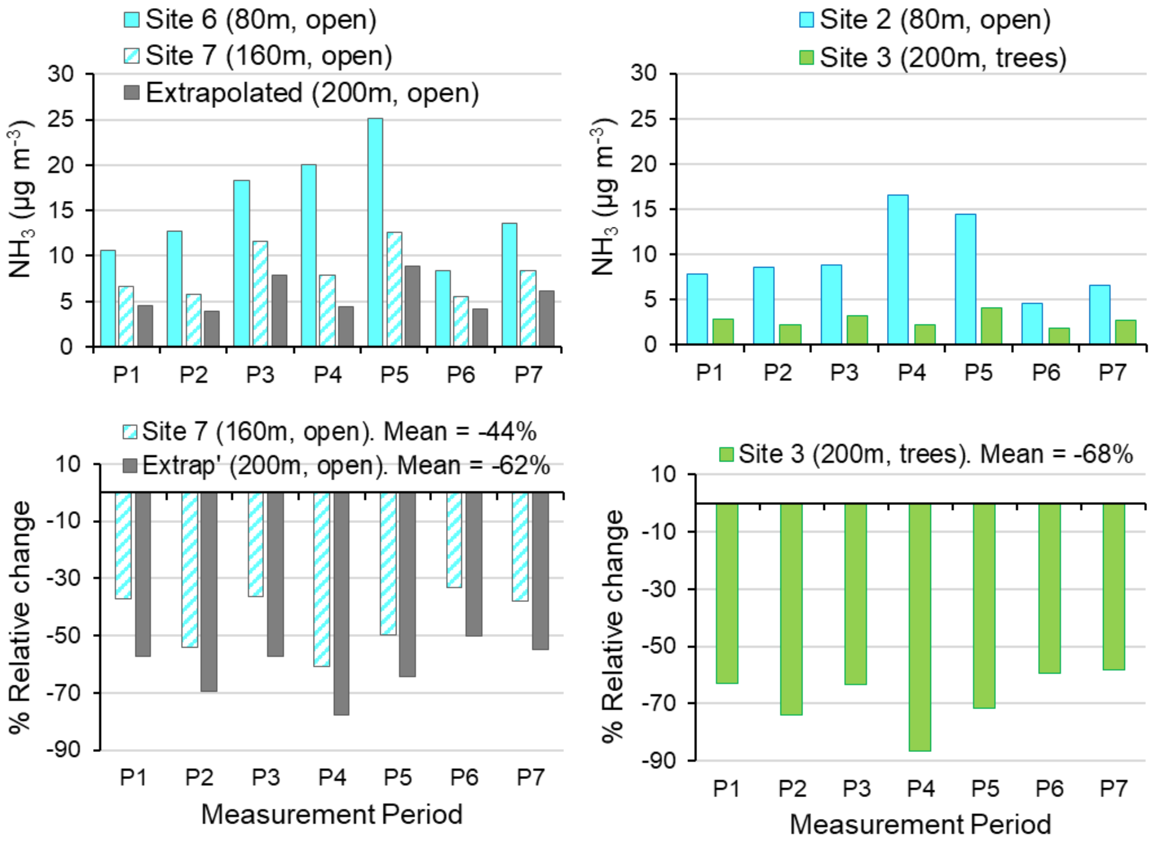


Figure 18: *(TOP) Comparison of NH_3 concentrations between paired sites in the two parallel transects. Transect 2: sites 6 (80m, open), 7 (160m, open, and extrapolated concentrations at 200m, open) and Transect 1 sites 2 (80m, open), 3 (200m, trees). (BOTTOM) relative change in NH_3 concentrations, 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*

Corticulous (bark) Lichen Survey

The lichen sampling was carried out along the NH_3 transects (Figure 28). The results for this farm are shown in Table 13 with details as in

Table 14. Further tree species: L larch; S sycamore. The NAQI values along the Dairy 2 transect are plotted in Figure 19. The NAQI values for Dairy 2 average very slightly higher than those for Dairy 2 (1.44 and 1.42 respectively). The overall result is similar to Dairy 2, but they do differ in detail. Examination of Figure 2 shows that sites 1, 5, 6 and 7, situated in open parkland have high NAQI values (>1.4) while sites 2, 3 , 4 and 8 situated adjacent to, or within woodland are more varied. NAQI values at sites 2 and 3 are high but those of sites 4 and 8, situated further away from the farm are lower, more in line with the control site 10. Again, oak and birch could not always be found and alder, larch and sycamore has to be substituted at three of the sites. This was unfortunate since the above-mentioned sites 4 and 8 were on alder and larch respectively. Both have an acid bark however although they also tend to have poorer

floras in general so no firm conclusions can be drawn relating the NAQI to local emissions of ammonia at these two sites. Sycamore is the least favourable tree for a NAQI study since it has a moderately basic bark. This means that its flora tends, even in an unpolluted district, to have an elevated NAQI value although this is not apparent in Figure 2.

More non-target species were found at Dairy 1 than at Dairy 2 and they include several interesting foliose and squamulose lichens (Table 14). Species of interest include *Flavoparmelia soredians*, a bright yellow-green foliose species of trunks rather than branches. It was found on three of the trees. This lichen is usually seen near the coast and has been rarely reported in Cumbria until recently. It appears to be rapidly expanding its range and is generally regarded as fairly N-intolerant so its occurrence at the site 2 oak was surprising. Other intolerant taxa were also found at this site, namely *Ramalina fastigiata*, *Rinodina sophodes* (in a poor condition) and *Tuckermanopsis chlorophylla*. Another interesting lichen, once considered a good indicator of clean air, was *Normandina pulchella.* This species did not occur on any of the target trees but was noted on mossy sycamore within the woods. It is another lichen that appears to have extended its range and is now common throughout Cumbria. It is perhaps represented by a more pollution tolerant strain. There was no surprise in finding the filamentous green alga *Klebsormidium crenulatum*. It was seen on branches at site 8 and was also noted on a fence rail at Dairy 1 Farm. It is considered a good indicator of high atmospheric NO_X (Frahm, 1999). Although restricted to acidic rocks, wood and bark, it can cover large areas and has been seen smothering lichens in some areas through its rapid growth. This alga was hardly known in Britain 30 years ago but is now found throughout the UK lowlands.

Table 13: Lichen survey results for Dairy 2 Farm

Site No.	LIS	NAQI	$[NH_3]$ µmol m^{-3}	Tree species	Tree position
1	-2.4	1.44	0.33	O	36444 45324
2	-3	1.59	0.42	O	36473 45287
3	-3	1.59	0.42	S	36592 45345
4	-1.2	1.14	0.18	A	36767 45389
5	-2.6	1.49	0.36	O	36437 45392
6	-3	1.59	0.42	O	36471 45334
7	-2.6	1.49	0.36	O	36546 45394
8	-1.8	1.29	0.25	L	36681 45416
9	-2.6	1.49	0.36	O	36817 45465
10	-1.6	1.24	0.23	O	36346 45656

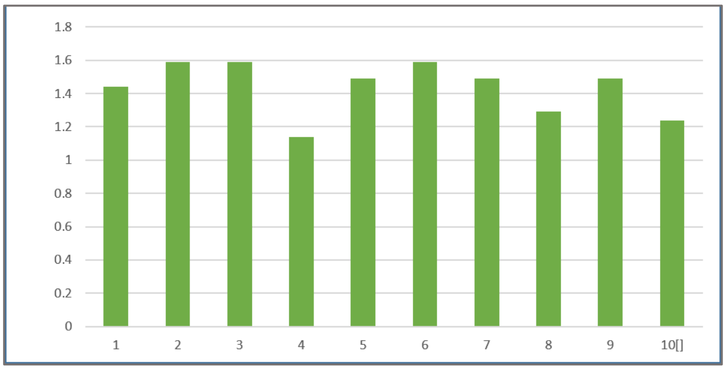


Figure 19: NAQI (nitrogen air quality index) values for Dairy 2

Table 14: Species list at Dairy 2 and presence at each site transect

Species	Site
Arthonia pruinata	2
Candelaria concolor	8
Flavoparmelia soredians	1, 2, 10
Haematomma ochroleucum s.l.	4
Hypnum cupressiforme	7
Hypotrachyna afrorevoluta	8
Klebsormidium crenulatum	8
Lecanora carpinea	9
Lecanora chlarotera	2
Lecanora expallens	7
Melanelixia glabratula	2
Opegrapha vulgata	1
Physcia aipolia	4
Ramalina farinacea	3, 7
Ramalina fastigiata	2
Rinodina sophodes	2
Tuckermanopsis chlorophylla	2

Modelling

Six measurement periods were recorded at Dairy 2 from August to October and their corresponding modelled wind roses are shown in Figure 6. All periods were approximately 2 weeks in length starting in early August, apart from Period 4 which was a 5 day period. Winds were mainly from the west/south west sector, with north-easterlies in Period 1 and north-westerlies in Period 4. Table 15 shows the change in concentration between two sampling points before and after a woodland. At this farm there were two transects where woodlands occur – between sampling point 2 and 3, and 7 and 8 (Figure 14). The SCAIL (model) vs ALPHA (measured) columns represents the concentrations and the final column is the difference in the change of concentration between the sampling points. The concentration values between the model and what was measured are comparable. The hypothesis is that the SCAIL model will show a slower reduction in concentrations, than the measured, across the same distance since the model assumes no trees are present between the source and a receptor. For most of the periods and across both transects this is borne out, as the positive % difference indicates the measurement concentrations have changed more, and that this could be down to the presence of trees having a deposition and dispersion effect on the ammonia plume. However, for Period 1 this is not borne out and is likely to be down to winds coming from the opposite direction to the source (north east) taking the ammonia plume away from the woodland. Additionally, from points 3 to 4 and points 8 to 9 the measured concentrations often go up - always for point 9. This is likely due to other ammonia sources nearby raising the concentration at these points. Points 4 and 9 are outside the woodland and are in the vicinity of grazed fields and other potential ammonia sources.

Table 15: Modelled (SCAIL) vs measured (ALPHA) NH_3 concentrations in µg m-3 for Dairy 2 farm for 6 periods, % change in ammonia reduction due to the woodland. A +ve % difference indicates the measured % change is higher (Green is the treebelt)

Period	Sampling Site	NH_3 SCAIL	ALPHA	SCAIL % conc △	ALPHA % conc △	SCAIL vs ALPHA
Period 1	1	10.07	10.80			
Period 1	2	4.72	7.80	68%	63%	**Difference**
Period 1	3	1.50	2.90			**-5%**
Period 1	4	0.56	3.65			
Period 1	5	15.87	17.09			
Period 1	6	6.84	10.63			
Period 1	7	2.43	6.68	67%	61%	**Difference**
Period 1	8	0.79	2.63			**-7%**
Period 1	9	0.42	4.34			
Period 1	10	1.07	9.12			
Period 2	1	14.41	12.33			
Period 2	2	6.78	8.58	69%	74%	**Difference**
Period 2	3	2.11	2.24			**5%**
Period 2	4	0.76	2.18			
Period 2	5	23.49	22.07			
Period 2	6	10.37	12.69			
Period 2	7	3.78	5.84	69%	78%	**Difference**
Period 2	8	1.16	1.31			**8%**
Period 2	9	0.57	2.45			
Period 2	10	2.42	6.08			
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			
Period 6	1	7.63	6.87			
Period 6	2	3.37	4.59	57%	59%	**Difference**
Period 6	3	1.46	1.87			**3%**

Period 6	4	0.58	2.21			
Period 6	5	19.01	13.19			
Period 6	6	8.14	8.35			
Period 6	7	2.97	5.57	69%	75%	**Difference**
Period 6	8	0.91	1.38			**6%**
Period 6	9	0.45	2.27			
Period 6	10	2.93	12.28			

3.1.3 Poultry 1

Poultry 1 has about 100m depth of trees downwind from the poultry house which from previous modelling should be good for dispersion and recapture of ammonia (Figure 20). The trees are 11 years old and the plantation has long sides parallel to prevailing wind. At the farm there are 3 sheds in total (26k birds) with 1 of 3 sheds roof ventilated (12k birds).

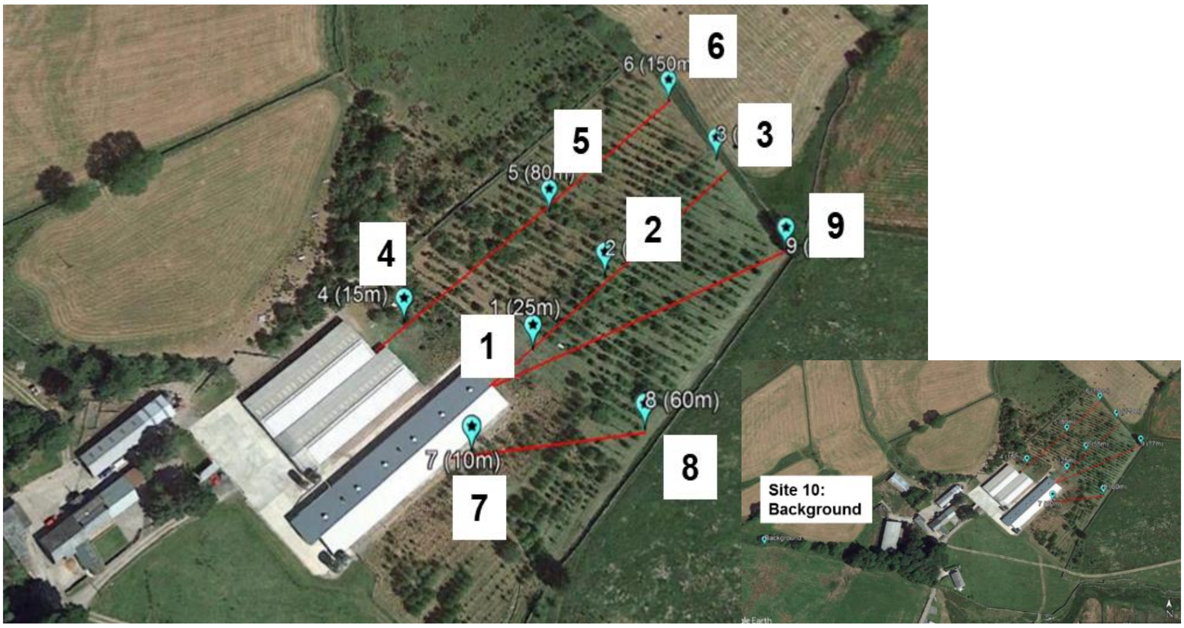


Figure 20: Poultry 1 poultry farm with (LHS) locations of NH_3 monitoring points. The background site (10) is located to the NNE of farm, between two fields (inset image)

Ammonia monitoring

Site 1 had the largest NH_3 concentrations (mean = 414 µg NH_3 m^{-3}, 24% higher than site 4 (sheds 2 and 3 with 14,000 birds). NH_3 declined rapidly in concentrations with distance along the two wooded transects: sites 1 – 3 downwind of shed 1, and sites 4 – 6 downwind of shed 2 and 3. The largest decrease occurred <80 m. At shed 1, NH_3 concentrations declined 11-fold from 414 µg NH_3 m^{-3} (193 – 623 µg NH_3 m^{-3} at site 1 (25 m NE of shed) to 36 µg NH_3 m^{-3} (13.5 - 70 µg NH_3 m^{-3}) at site 2 (55 m NE of shed). NH_3 concentrations behind the tree treebelt: 95 m (site 3, mean = 8.2 µg NH_3 m^{-3}) and 135 m (site 6, mean = 7.7 µg NH_3 m^{-3}) were near background levels (site 10, mean = 5.7µg NH_3 m^{-3}). The high NH_3 observed at the background site can be attributed to both cattle and land spreading emissions that are known to occur in the area, contributing to elevated local NH_3 background concentrations, as well as some enhancement from the poultry emissions.

Table 16: Monitored NH_3 concentrations with ALPHA® samplers at Poultry 1.

Site ID		Measured NH_3 Concentrations with (µg NH_3 m^{-3})						
		P1	P2	P3	P4	P5	Mean	SD

	Distance from shed (m)	**06/08 - 19/08**	**19/08 - 03/09**	**03/09 - 25/09**	**25/09 - 30/09**	**30/09 - 19/10**		
1	25	528	397	623	193	332	**414**	168
2	55	24.1	48.7	69.7	13.5	28.5	**36.9**	22.4
3	120	10.4	8.6	12.2	4.2	5.8	**8.2**	3.3
4	15	*nd*	433	512	54.8	255	**314**	203
5	80	20.1	26.4	26.8	9.1	14.4	**19.4**	7.7
6	150	10.6	8.3	9.3	4.0	6.4	**7.7**	2.6
7	10	*nd*	173	90.4	115.2	129	**127**	34.8
8	60	16.8	13.5	20.8	12.1	24.0	**17.4**	5.0
9	120	7.9	6.4	11.0	4.6	4.8	**6.9**	2.6
10	-	8.7	2.4	6.2	5.6	*nd*	**5.7**	2.6

nd = no data (lost, or rejected due to sampling issues)

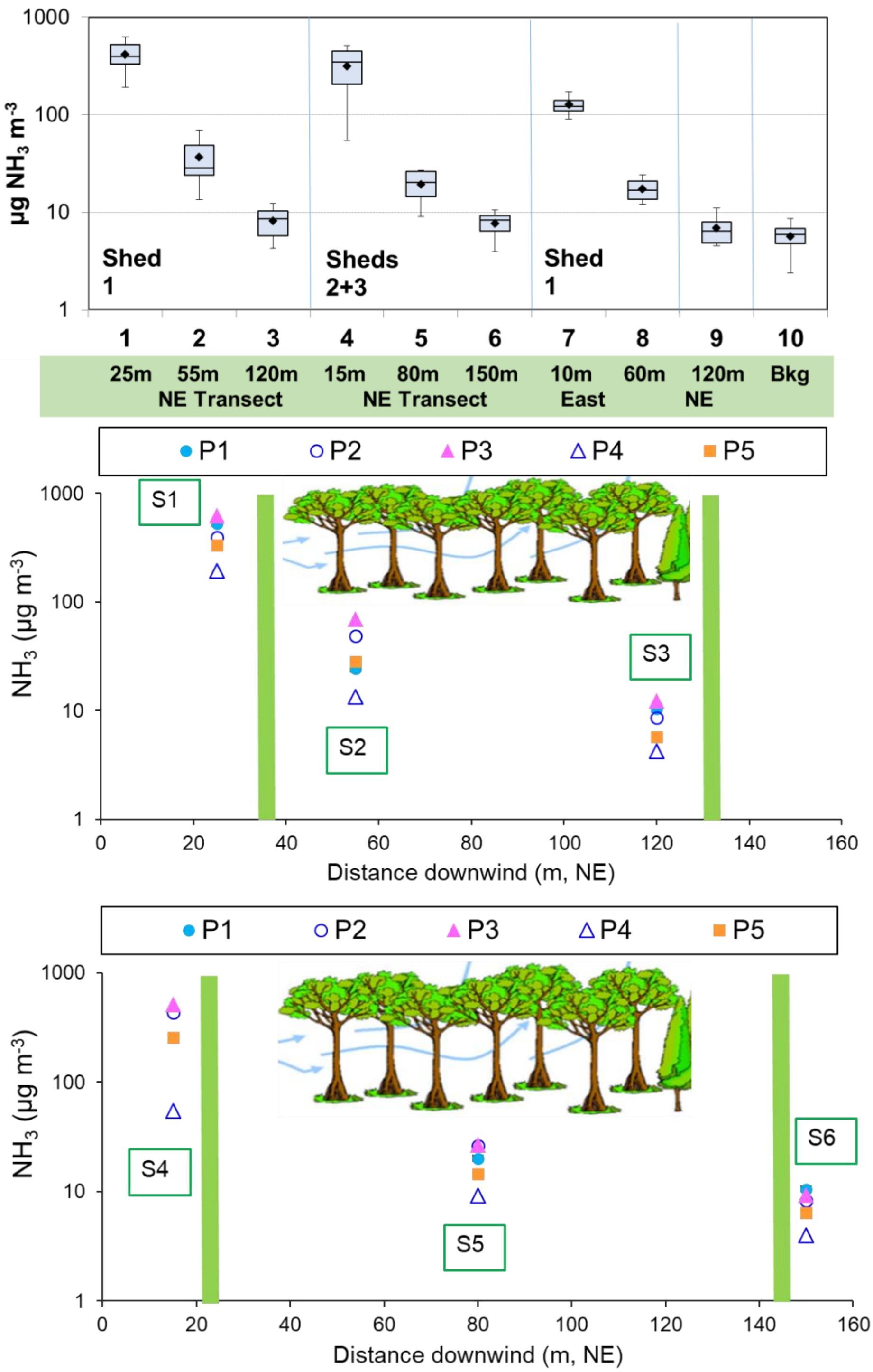


Figure 21 NH_3 concentrations along 2 parallel transects downwind of farm showing large decline in concentrations within 80 m from source (poultry buildings). NH_3 concentrations are plotted on a log scale to provide better visualisation of data across the wide range of concentrations

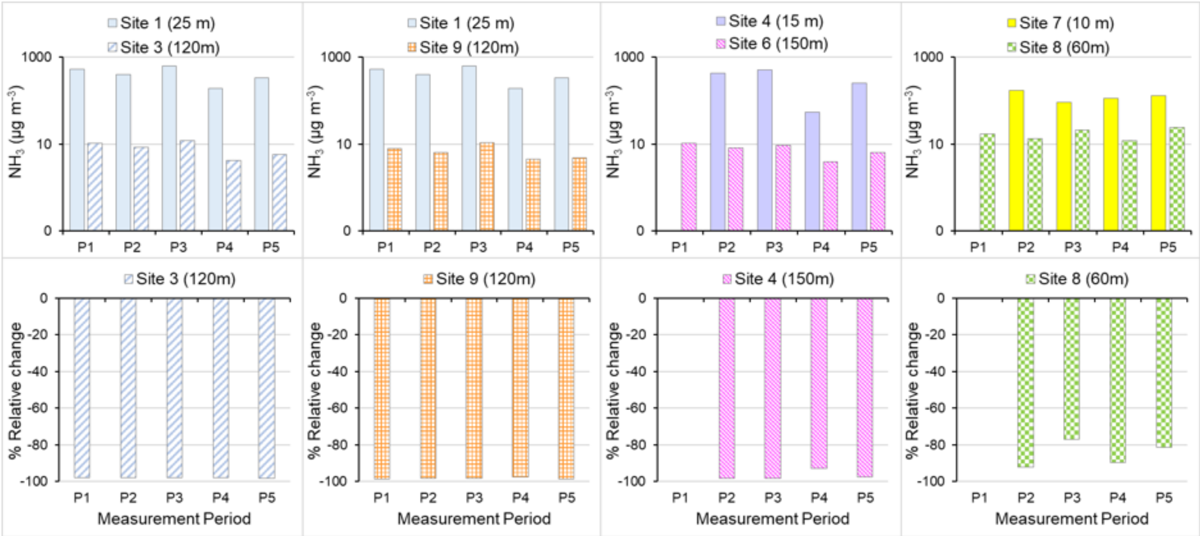


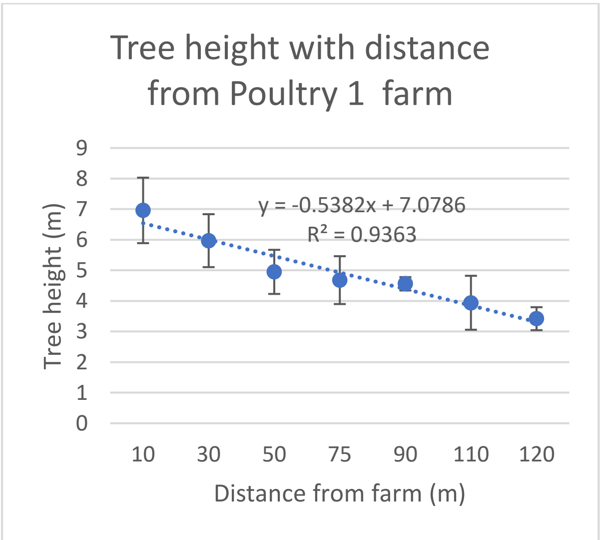
Figure 22 (Top) Comparison of NH_3 concentrations between paired sites before and after trees: 1v3, 1v9, 4v6 and 7v8), (Bottom) relative change in concentrations, showing large reduction in concentrations (> 81 %) at sites behind the tree treebelt.

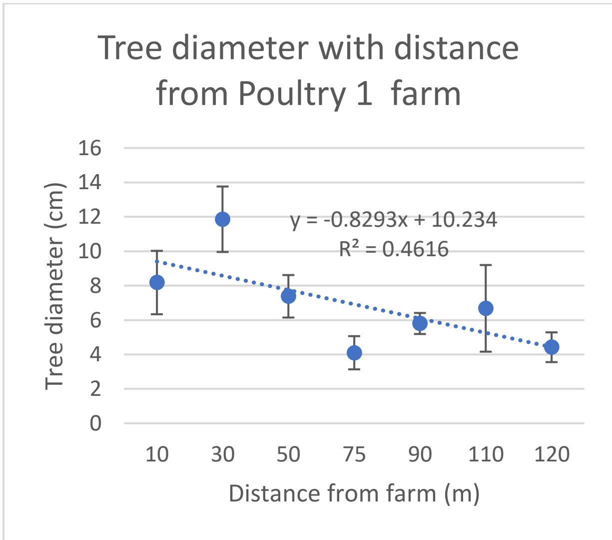
Table 17 Relative changes in concentrations of NH_3

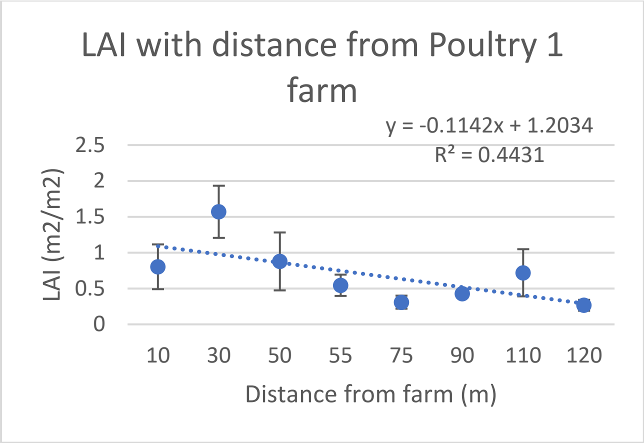
	Site 3	*Site 9*	*Site 6*	*Site 8*
Mean Rel. change (%)	*-98.0 %*	*-98.2 %*	*-96.6 %*	*-85.0 %*
Re, change per m of trees	*-1.0 % / m*	*-1.0 % / m*	*-1.0 % / m*	*-1.7 % / m*

Tree growth, leaf morphology and nutrient uptake

At Poultry 1, sampling was carried out at all points under trees where ammonia was also measured. Additional points marked with red were added for tree assessments to increase the number of points along the transects (Figure 20 RHS). Tree height and diameter significantly decrease with distance away from the Poultry 1 farm. Tree diamater is more variable parameter than tree height. Tree LAI decrease with distance from Poultry 1 farm. Tree canopy uptake of nitrogen decreases up to three times with distance from Poultry 1 farm from on average 30 kg N/ha at 10 m down to less than 10 kg N/ha at 120 m away from the farm.







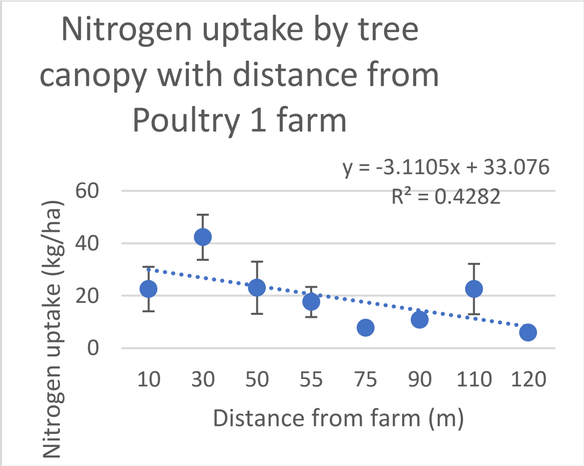


Figure 23: Tree height, diameter, LAI and canopy nitrogen uptake with distance away from Poultry 1 farm. Mean values from at least 5 trees of different species for each point in transect are presented and vertical bars are standard errors of the mean. Indicative

Modelling

Figure 6 shows the wind roses for the two week measurement periods from August to October at Poultry 1, noting that Period 4 is only 5 days in length. The wind directions are variable across the periods with weak winds in Period 1 and strong northerlies/north westerlies in Period 4 and 5. Period 3 represents the most suitable wind direction for comparing model and measured results as the winds are coming from the south west and pick up the plume and take it through the canopy in the direction of the transects. Table 18 shows the % change in concentrations between two sampling points before and after a treebelt. The SCAIL ammonia concentration is a combination of adding the model outputs from both sheds (with fans and side ventilated). For this farm there are two transects where treebelts occur – between sampling point 1 and 3, and 4 and 6 (Figure 21 TOP). Positive % changes were observed in all the sampling periods in both transects with transects 1 to 3 from the longer shed (with roof fans) showing the strongest correlation. Importantly, the concentration values between modelled and measured are very different at the very near sampling points 1 and 4, by an order of x10. This may be due to the sheds themselves having been built around 4 metres lower than the surrounding ground and hence the fans/vents are much lower. Remodelling in SCAIL applying a lower building height was examined to see if values at these near points increased. However, reducing the height of the sheds in the model only increased the concentrations by around 10%. Flow-rate of the shed with fans could be higher than in practice, but neither height nor flow rate can explain the differences in the modelled and measured results at Point 1 and 4. Other near-building effects like downwash may be affecting these ‘close to source’ monitoring points.

Table 18: Modelled (SCAIL) vs measured (ALPHA) NH_3 concentrations in µg m-3 for Poultry 1 farm for 5 periods. % change in ammonia reduction due to the woodland. A +ve % difference indicates the measured % change is higher (Green is the treebelt)

Period	Sampling Site	NH_3 SCAIL	ALPHA	SCAIL % conc △	ALPHA % conc △	SCAIL vs ALPHA
Period 1	1	44.26	527.89			
Period 1	2	21.89	24.1	75%	98%	**Difference**
Period 1	3	11.00	10.37			**23%**
Period 1	4	90.68	145.14			
Period 1	5	21.57	20.14	88%	93%	**Difference**
Period 1	6	10.79	10.56			**5%**
Period 1	7	43.46	140.58			
Period 1	8	16.38	16.84			
Period 1	9	9.79	7.95			
Period 1	10	4.97	8.67			
Period 2	1	36.99	397.00			
Period 2	2	16.13	48.67	79%	98%	**Difference**
Period 2	3	7.69	8.61			**19%**
Period 2	4	71.35	433.20			
Period 2	5	15.70	26.40	90%	98%	**Difference**
Period 2	6	7.26	8.31			**8%**
Period 2	7	30.66	173.30			
Period 2	8	16.83	13.50			
Period 2	9	7.84	6.39			
Period 2	10	2.87	2.39			
Period 3	1	34.10	622.86			
Period 3	2	14.07	69.74	81%	98%	**Difference**
Period 3	3	6.39	12.23			**17%**
Period 3	4	73.45	512.13			
Period 3	5	13.72	26.77	92%	98%	**Difference**
Period 3	6	6.01	9.30			**6%**
Period 3	7	30.79	90.40			
Period 3	8	14.84	20.80			
Period 3	9	6.40	11.00			
Period 3	10	2.67	6.18			
Period 4	1	34.95	192.58			
Period 4	2	15.81	13.52	74%	98%	**Difference**
Period 4	3	9.08	4.24			**24%**
Period 4	4	90.80	54.75			
Period 4	5	23.03	9.10	87%	93%	**Difference**
Period 4	6	11.74	3.98			**6%**
Period 4	7	23.13	115.19			
Period 4	8	8.97	12.05			
Period 4	9	4.80	4.57			
Period 4	10	1.01	5.62			
Period 5	1	28.44	331.81			
Period 5	2	13.45	28.47	76%	98%	**Difference**
Period 5	3	6.88	5.77			**22%**
Period 5	4	49.88	254.85			
Period 5	5	12.79	14.41	86%	97%	**Difference**
Period 5	6	6.88	6.40			**11%**
Period 5	7	26.89	129.02			
Period 5	8	13.96	24.04			
Period 5	9	6.69	4.83			
Period 5	10	1.42	6.18			

3.1.4 Poultry 2

Ammonia monitoring

Poultry 2 farm is a single poultry shed and treebelts planted on 3-sides of the shed (Figure 24), which in theory is a simple case. The prevailing wind in the UK is mostly from the SW. Planting is also < 35m from the housings to maximise the capacity of the treebelt for NH_3 capture. The farm has 2k birds in a single shed which has natural ventilation. The landscape allows for open vs wooded transects for monitoring. Having transects between two points of similar length and orientation, one with trees and one without, makes for a good comparison.

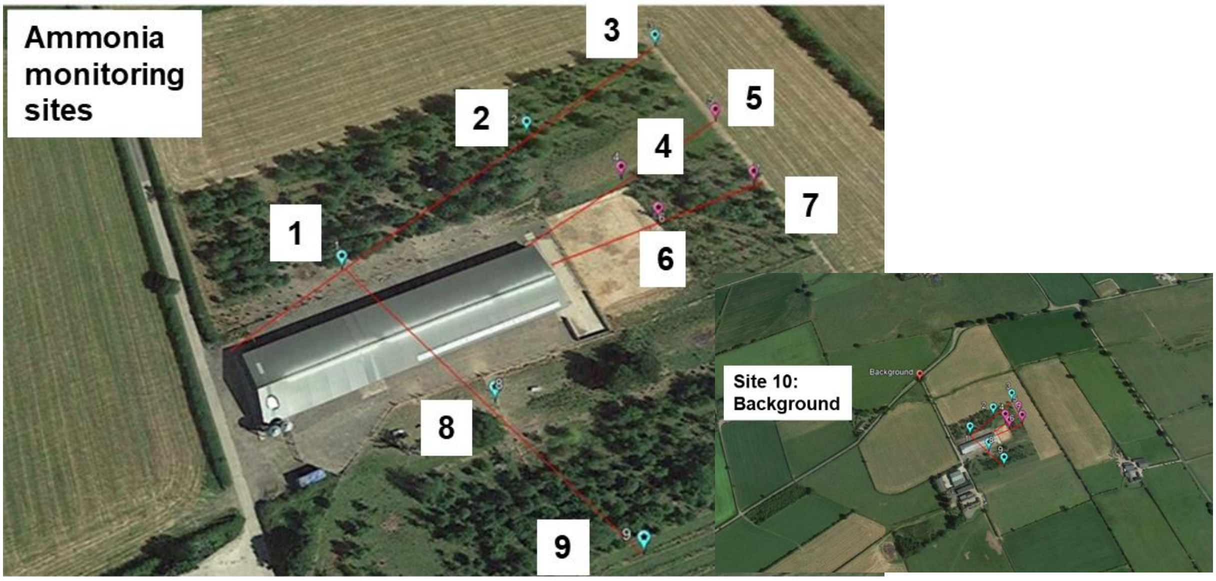


Figure 24 Poultry 2 poultry farm showing locations of NH_3 monitoring points for a detailed spatial assessment of the site. The background site (10) is located to the NNE of farm (inset image).

Table 19: Monitored NH_3 concentrations with ALPHA® samplers at Poultry 2.

Site ID	Distance from shed (m)	Measured NH_3 Concentrations with (µg NH_3 m^{-3})						
		***P1**	**P2**	**P3**	**P4**	**P5**	**Mean P2 – P5**	**SD P2 – P5**
		04/08 - 18/08	**18/08 - 03/09**	**03/09 - 24/09**	**24/09 - 30/09**	**30/09 - 15/10**		
1	35	4.8	22.6	53.6	57.5	52.7	**46.6**	16.1
2	110	4.1	7.6	13.9	7.1	11.1	**9.9**	3.2
3	165	2.1	3.5	8.3	4.4	4.3	**5.1**	2.2
4	35	2.2	11.1	52.4	6.4	23.6	**23.4**	20.7
5	70	2.4	5.9	31.1	4.6	12.9	**13.6**	12.2
6	35	2.4	9.7	52.1	11.4	46.8	**30.0**	22.6
7	70	2.4	4.3	20.8	4.3	20.2	**12.4**	9.3
8	20	2.7	10.3	19.7	55.8	51.0	**34.2**	22.6
9	70	2.5	3.5	5.0	15.7	9.3	**8.4**	5.5
10	-	2.5	5.6	3.8	4.0	2.9	**4.1**	1.1

*Note: *P1 (Period 1) = poultry housing empty between 04/08 – 13/08. Birds were housed at Poultry 2 on August 13th.*

The highest NH_3 concentrations were detected at site 1 on the north side of the poultry shed (mean = 47 µg NH_3 m^{-3}; periods 2-5) (Table 19). This declined rapidly with distance along the downwind transect through the trees to a mean concentration of 5.1 µg NH_3 m^{-3}; (periods 2 - 5) at site 3, approaching background concentrations of site 10 (mean = 4.1 µg NH_3 m^{-3}; periods 2 – 5).

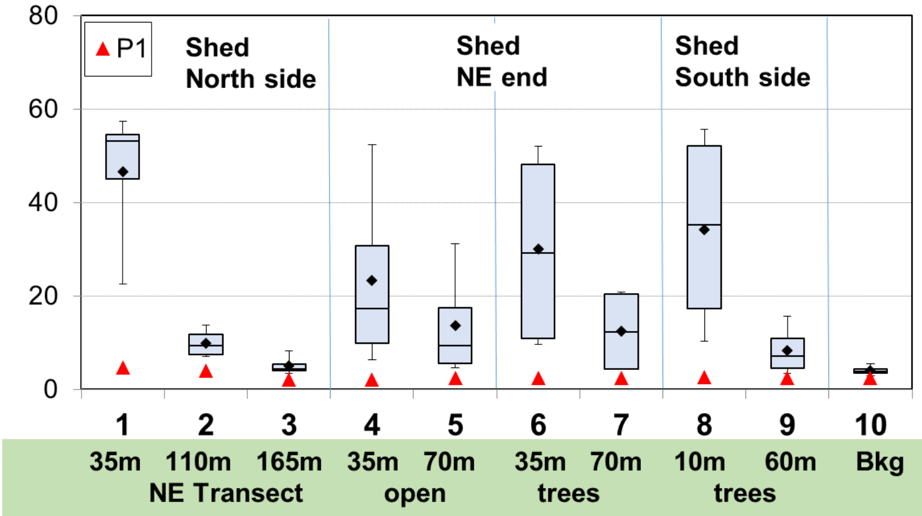


Figure 25: Boxplot summarising concentrations measured at the 10 locations on Poultry 2 farm from 5 measurement periods (05/08/2020 and 15/10/2020). Period 1 is plotted separately as this was an "empty" period before population of the poultry house. Whiskers are the min and max measured concentrations. Bkg = Background site 10.

A gap in the treebelt offered the opportunity to compare a wooded transect (sites 6, 7) with an open transect (sites 4, 5). Sites 4 and 6 are both located 35 m from the NE end of the shed (Figure 26). NH_3 concentrations at the two sites were similar in periods 1 to 3, but deviated in periods 4 to 5. The difference in concentrations in the last 2 periods is most likely due to change in directions of prevailing winds. This is supported by changes in concentrations at Site 8 (20m south of the shed) relative to Sites 4 and 6 (Figure 26). In the last 2 periods, NH_3 concentrations at Site 8 changed from being smaller, to being larger than both Sites 4 and 6. Since concentrations at Site 6 also became larger than Site 4, then this would indicate winds coming from the west/northwest.

Site 5 is 35 m NE of site 4, in a 10 m wide gap in the treebelt, whereas site 7 is located 35 m NE of site 6, behind the 35 m treebelt. NH_3 concentrations at site 5 (mean = 13.6 µg NH_3 m^{-3}; periods 2 - 5) was larger than at site 7 (12.4 µg NH_3 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 27). The analysis showed larger reduction in concentrations at site 7 (behind 35m treebelt, than at site 5, with no trees. 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 capture NH3 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.

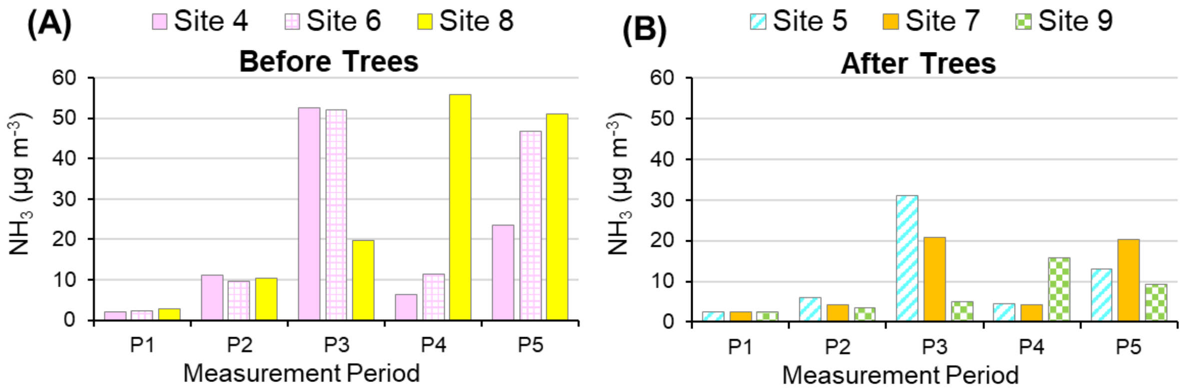


Figure 26: Monitored NH_3 concentrations at (A) sites 4, 6 and 8 before trees, and (B) sites 5, 7 and 9 behind the tree treebelt.

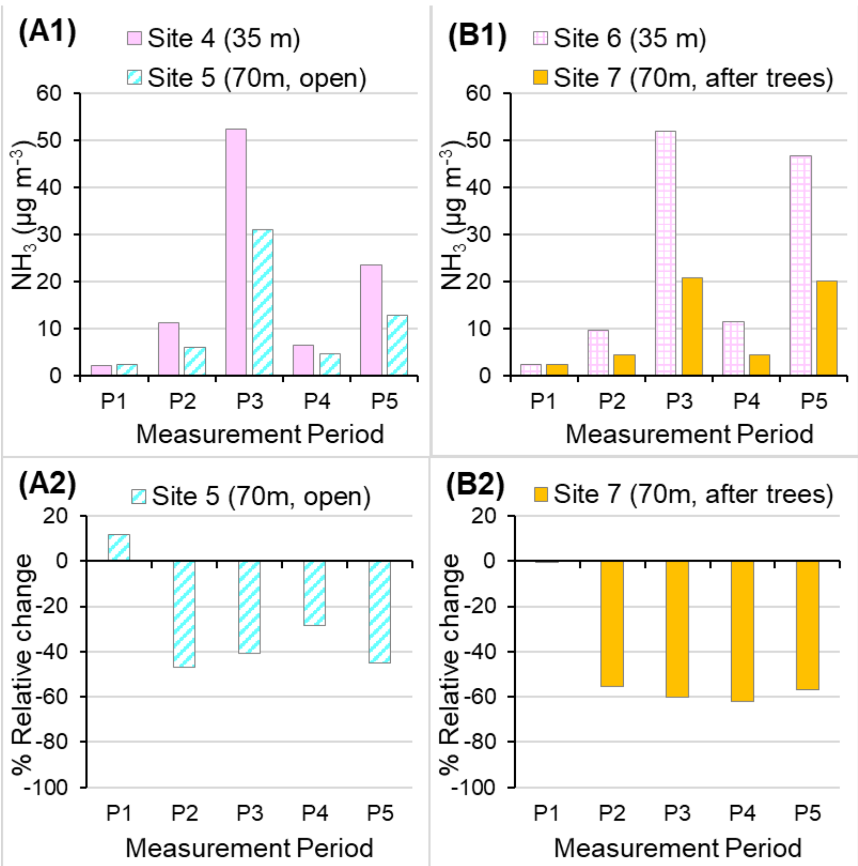


Figure 27: (TOP) Comparison of NH_3 concentrations between sites in an open transect (A1) with other sites in wooded transect (B1). (BOTTOM) Relative change in concentrations, showing larger reduction in concentrations at sites located behind the tree treebelt (B2: mean = -50.8 %, n = 4)) than at site 5, with no trees (A2: mean = -40.3 %, n = 4).

Tree growth, leaf morphology and nutrient uptake

Figure 28 shows that the tree height and diamater decline with distance away from the farm and tree height and diamater significantly declined between 10 m and 30 m, 70 m and 90 m away from the farm. Tree diameter shows much higher variability between species than tree height. Tree Leaf Area Index 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 down to 17 kg N/ha at 90 m distance away from the farm.

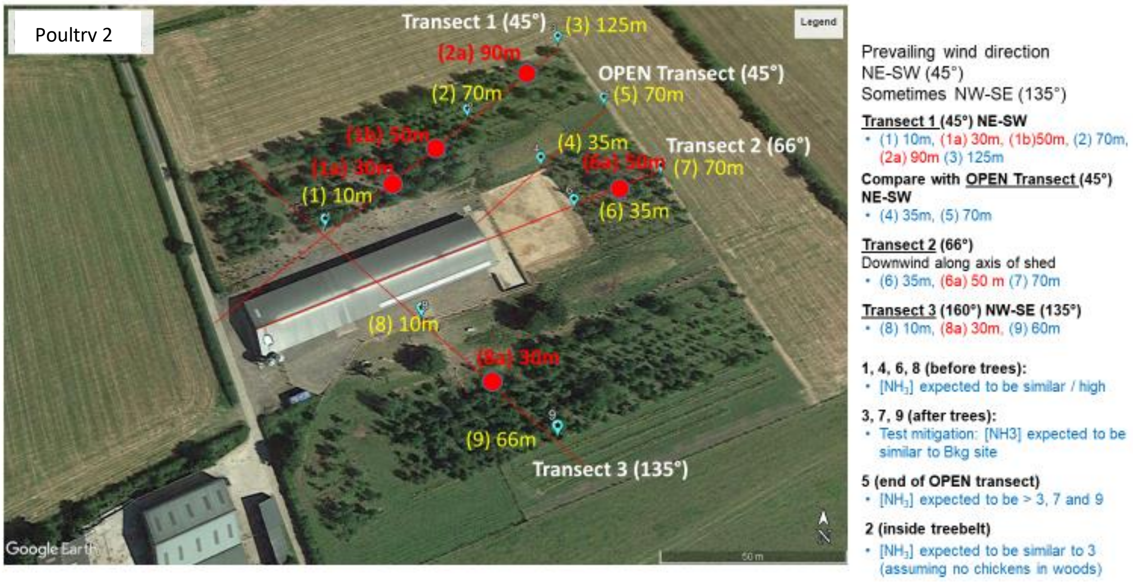
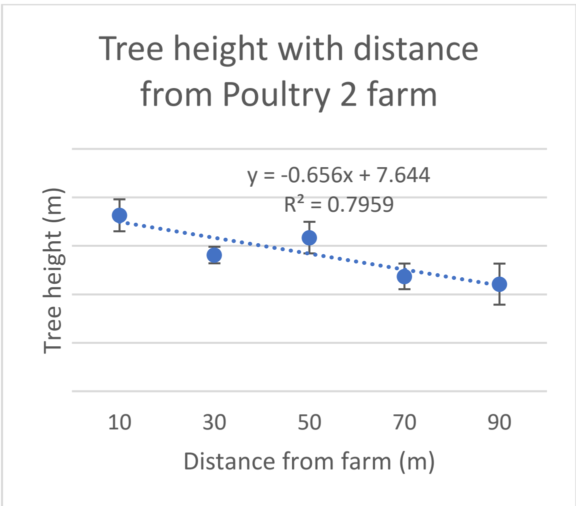
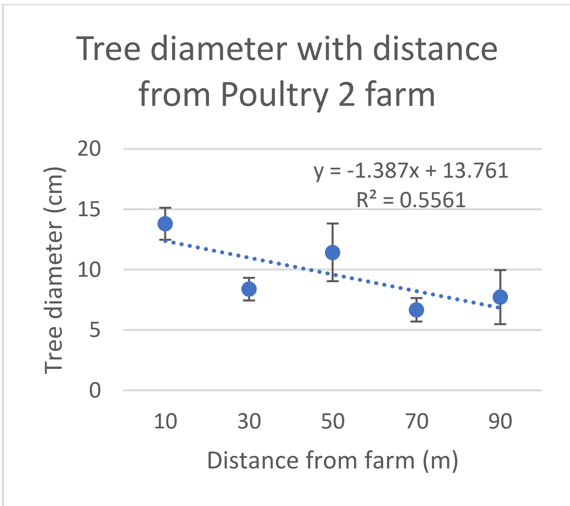
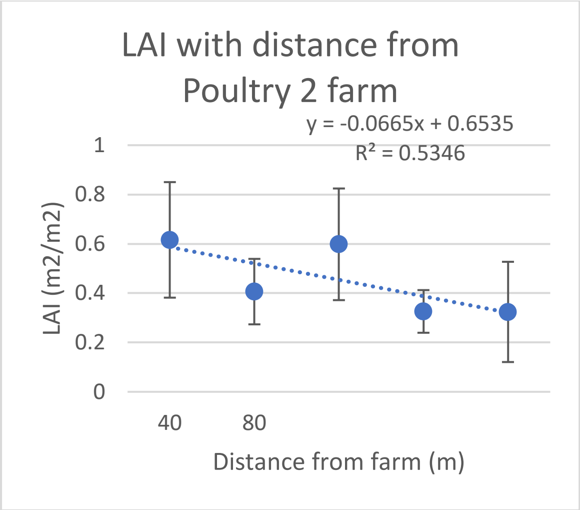


Figure 28: sampling was carried out at all points under trees where ammonia was also measured (map with transects provided by CEH). Additional points marked with red were added for tree assessments to increase the number of points along the transects.







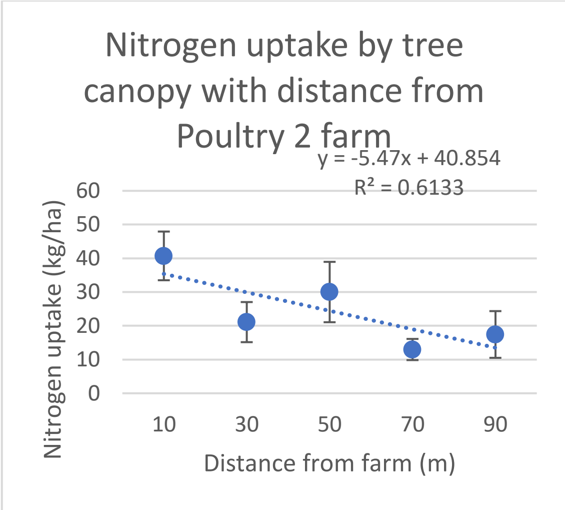


Figure 29: Tree height, diameter, LAI and canopy nitrogen uptake with distance away from Poultry 2 farm. Mean values from 5 to 10 trees of different species for each point in Transect 1 and 2 are presented and vertical bars are standard errors of the mean. Indicative linear relationships are drawn between tree parameters and distance from farm.

Modelling

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 south west of Poultry 2.

Table 20 shows the change in concentration between two sampling points before and after a treebelt and when no treebelt is present. For this farm there is a transect where a treebelt occurs, between points 6 to 7, and an open (no trees) transect between 4 to 5 (Figure 24). A third transect (wooded) was also assessed between points 8 and 9. 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 change in the measured concentrations. For Period 2 and Period 5 this is borne out as the difference between the respective changes in concentration is relatively small (2-4%). But for other periods, notably Period 4, the difference between modelled and measured was higher (17%). This could be explained by the wind direction during this period when winds from the south west (carrying the plume along the transect) were very infrequent. For transect 8 to 9 the difference between the modelled and measured change in concentrations is negative indicating that 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 south west of Poultry 2.

Table 20: Modelled (SCAIL) vs measured (ALPHA) for Poultry 2 for 4 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	NH_3 measure	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			
4	1	108.51	57.46			
4	2	13.64	7.06			
4	3	6.46	4.40			
4	4	16.56	6.45	46%	29%	**Difference**
4	5	9.02	4.60			**-17%**
4	6	15.88	11.43	44%	62%	**Difference**
4	7	8.90	4.34			**18%**
4	8	66.51	55.77	78%	72%	**Difference**
4	9	14.84	15.70			**-6%**
4	10	3.08	4.05			
5	1	40.14	52.68			
5	2	8.26	11.11			
5	3	3.65	4.31			
5	4	9.64	23.57	49%	45%	**Difference**
5	5	4.88	12.93			**-4%**
5	6	10.99	46.85	47%	57%	**Difference**
5	7	5.79	20.19			**10%**
5	8	36.22	50.99	84%	82%	**Difference**
5	9	5.90	9.33			**-2%**
5	10	0.83	2.87			

3.1.5 Poultry 4 and Poultry 3

These two farms are combined into a single study farm site, due to close proximity. Details are shown in Table 21.

Table 21: Details of Poultry 4 and Poultry 3 Farm

	Poultry 4	**Poultry 3**
tree-belt depths	100 m	25 m
tree ages	7 years	12 years
Orientation of shed	Long sides Perpendicular to prevailing wind. Long sides faces woodland Width of shed is the same as width of treebelt	Long sides parallel to prevailing wind. Gable end faces treebelt
Number of birds	32K	6K

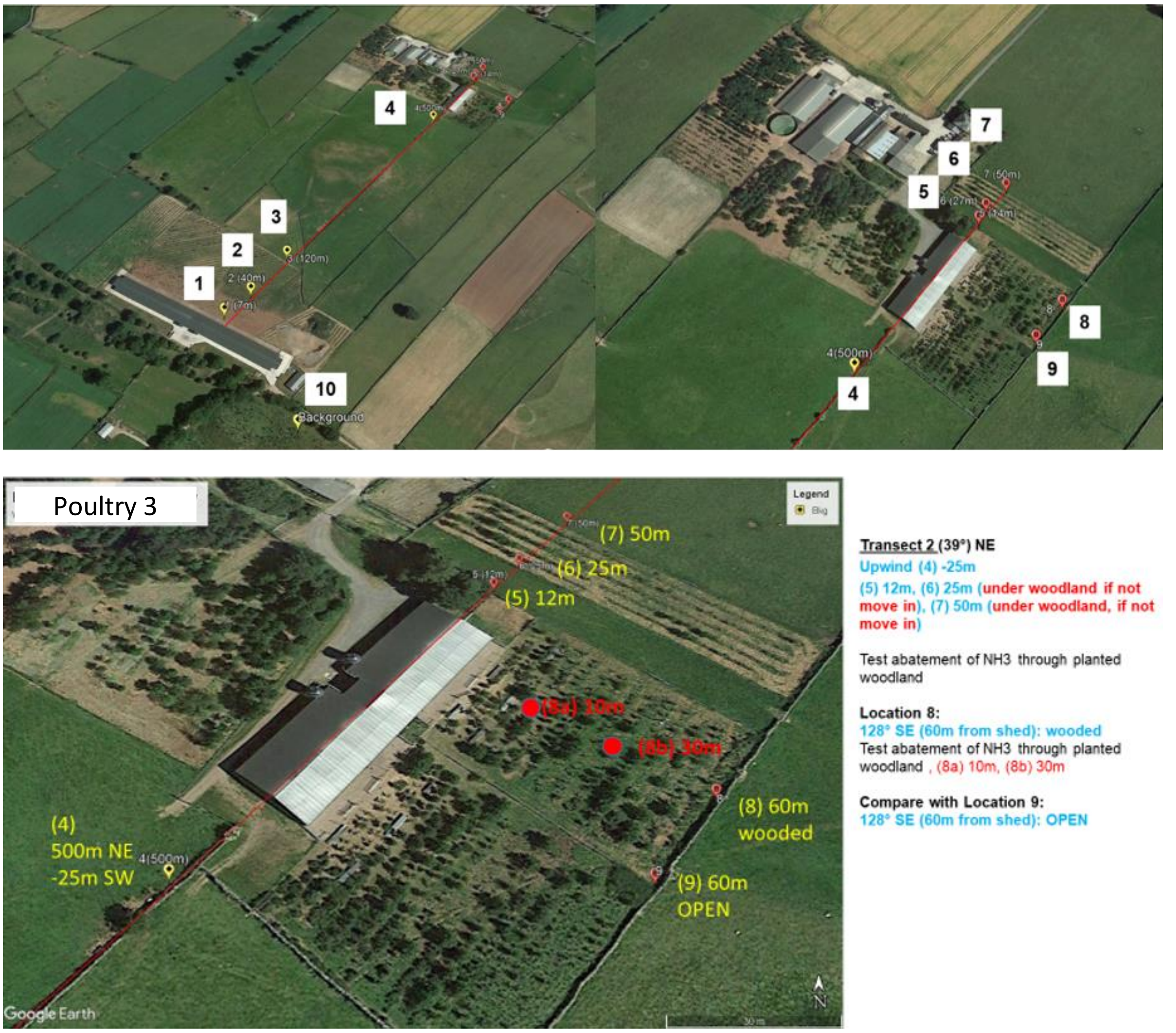


Figure 30 Poultry 4 (top left) and Poultry 3 monitoring locations. Bottom image shows Poultry 3 and extra sampling points (in red) of tree growth, leaf morphology and nutrient uptake measurements.

Ammonia monitoring

Table 22 shows the NH_3 concentrations over the seven sampling periods. Site 4 doubles up as the 4[th] site at end of transect sites 1-3 from Poultry 4, and as the upwind site for Poultry 3 at the same time. NH_3 concentrations along the Poultry 4 transect (sites 1 – 4) showed a significant decline in concentrations within 125 m from source (poultry building). Close to source NH_3 concentrations The concentrations was large close to the poultry housing, before the tree treebelt (site 1: 7m, mean = 186 µg NH_3 m^{-3}, range = 92 – 329 µg NH_3 m^{-3}, n = 7) and decreased 6-fold to a mean concentration of 29 µg NH_3 m^{-3} on the other side of the tree treebelt (site 3: 120 m, range = 18 – 38 µg NH_3 m^{-3}, n = 7). The concentrations at sites 3 (120 m) were similar to that at site 4 (500 m, mean = 22 µg NH_3 m^{-3}, range = 13 – 35 µg NH_3 m^{-3}, n = 7).

Figure 32 and Table 23 show the change in concentrations across the treebelt at Poultry 3 ((-41.0% to -62.5%)) and 4 (-75.0 % to -90.2 %). In Figure 33 and Table 24 a comparison was made between an open transect (gap in the treebelt) and completely wooded transect at Poultry 3. The ammonia measurements over the full seven monitoring periods (~14 weeks) showed a significant difference between the two sets of data indicating that the trees are having a mitigation effect on the ammonia plume. It is interesting to try and study the effects of changing season. A treebelt that is made up mainly of deciduous trees will be a great deal more porous during winter. The two photos in Figure 34 illustrates this, with site 2 becoming clearly more visible with onset of autumnal leaf drop.

The highest NH_3 concentrations were detected at site 1, located 7 m from the edge of the poultry shed, with a 3-fold increase in concentrations between period 1 (102 µg m^{-3}) and period 7 (329 µg m^{-3}). In each period, the concentrations declined rapidly with distance downwind through the trees to levels similar to background concentrations within 500m of the poultry shed. The relative change in NH_3 concentrations, in particular at sites 2 and 3, are expected to be smaller in the later periods, with onset of autumn leaf drop. However, the opposite was seen (Figure 36). It could be that during the wetter autumn months, there is increased moisture on the trees to capture and retain NH_3 and warrants further investigation. Continuation of measurements into the winter months would also have provided additional data to compare the wind reduction of the same treebelt both in summer and in winter.

Table 22: Monitored NH_3 concentrations with ALPHA® samplers at Poultry 4-Poultry 3.

Site ID	Farm	Distance from shed (m)	Measured NH_3 Concentrations with (µg NH_3 m^{-3})								
			P 1	**P 2**	**P 3**	**P4**	**P 5**	**P 6**	**P 7**	**Mean**	**SD**
			06/08 - 19/08	**19/08 - 03/09**	**03/09 - 17/09**	**17/09 - 02/10**	**02/10 - 14/10**	**14/10 - 29/10**	**29/10 - 11/11**		
1	Pol4	7	102	91.9	156	149	183	294	329	186	91.6
2	Pol4	40	53.2	38.6	58.5	52.8	48.3	95.9	103	64.3	24.8
3	Pol4	120	21.8	18.7	34.7	37.3	18.0	38.3	35.9	29.2	9.2
4	Pol4	500 (-50 upwind of P3)	23.2	18.9	16.0	35.2	28.0	22.6	13.2	22.4	7.4
5	Pol3	14	93.1	84.7	144	62.1	52.5	104	108	92.7	30.7
6	Pol3	27	63.2	68.6	97.7	65.1	40.6	79.0	65.4	68.5	17.3
7	Pol3	50	34.9	37.7	63.7	36.7	26.3	39.8	39.7	39.8	11.5
8	Pol3	80	19.5	17.7	*nd*[2]	29.1	46.0	21.8	23.9	26.3	10.4
9	Pol3	80	23.5	23.6	*nd*[2]	34.8	59.3	24.3	18.4	30.7	15.0
10	bk		14.8	nd[1]	13.3	25.1	27.2	16.9	8.6	17.7	7.1

nd[1] = no data (samples missing), nd[2] = no data (sampling issues)
Pol4 = Poultry 4, Pol3 = Poultry 3

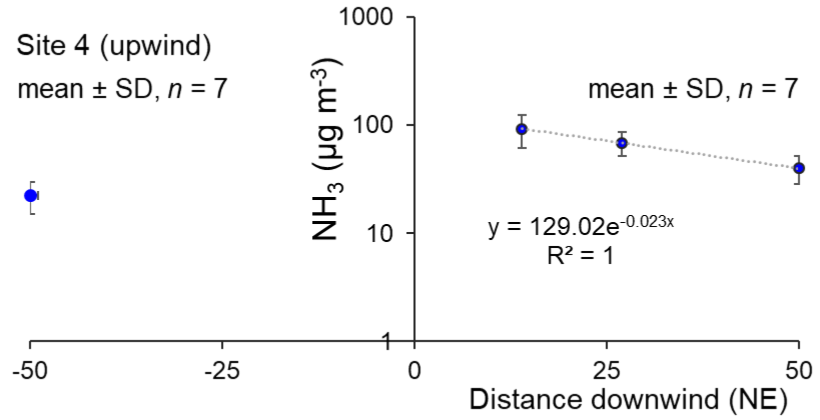


Figure 31 NH_3 concentrations (log scale) at sites 4 - 3 along transect downwind of Poultry 4 farm showing large decline in concentrations within 125 m from source (poultry building).

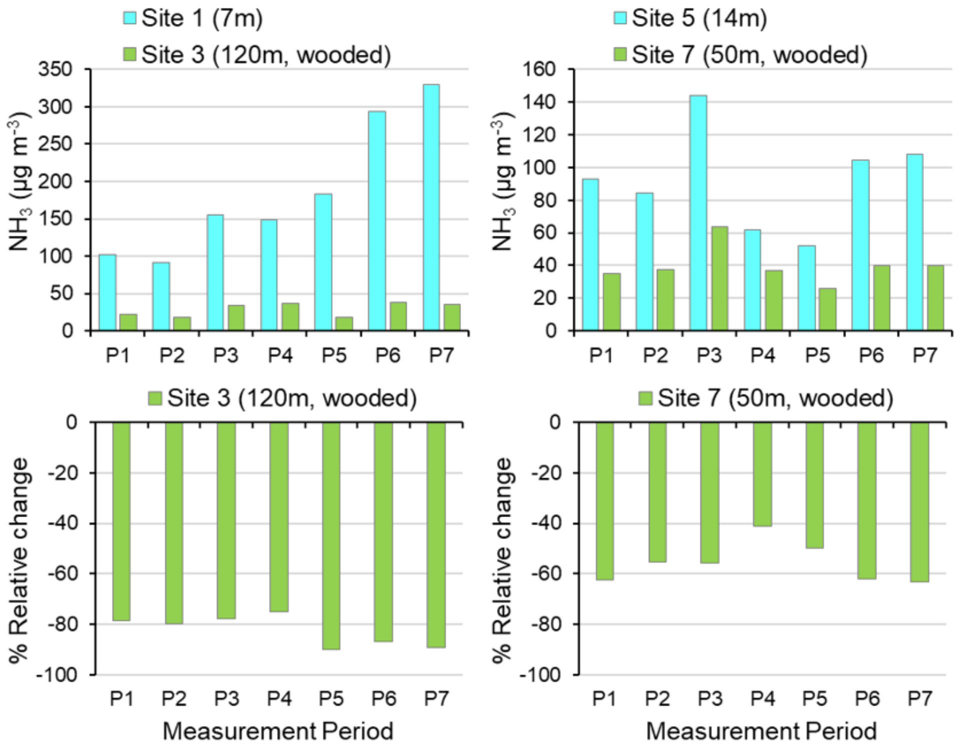


Figure 32 (Top) NH_3 concentrations between paired sites before and after trees: Poultry 4 sites 1 and 3; Poultry 3: sites 5 and 7. (Bottom) Relative change in NH_3 concentrations (reference = site before trees), showing large reduction in concentrations (> 81 %) at sites behind the tree treebelt

Table 23 Relative change in NH_3 concentrations at Site 3 and Site 7 Poultry 4 and Poultry 3 respectively

	Site 3	*Site 7*
Mean Rel. change (%)	*-82.5 % (-75.0 % - -90.2 %)*	*-55.7 % (-41.0% - -62.5%)*

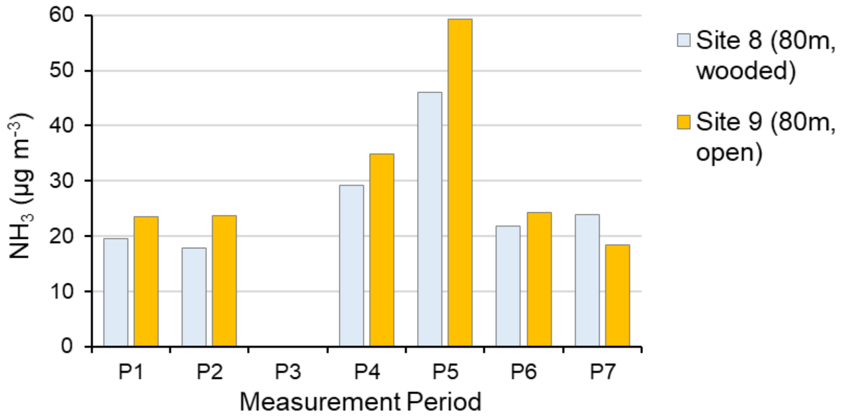


Figure 33 Comparison of NH_3 concentrations between paired sites located at same distance from poultry shed, in a gap in the treebelt (site 9) and behind treebelt (site 8)

Table 24 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* = 6)	26.33 (*n* = 7)
Site 9	33.11 (*n* = 6)	30.66 (*n* = 7)
Paired T-Test	P = 0.01	P = 0.07

**significant difference at $p < 0.01$*

Figure 34 Poultry 3 Site 2 before and after leave loss

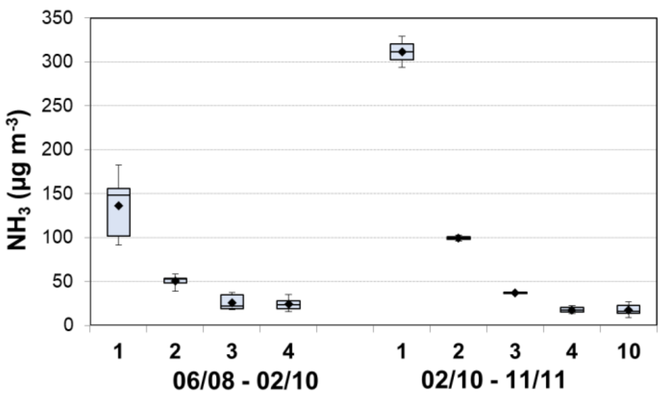


Figure 35 Boxplot comparing NH_3 concentrations measured at Poultry 4 (Sites 1 – 4) in late summer (06/08 – 02/10: Periods 1 – 5) and autumn (02/10 – 11/11, Periods 6 – 7).

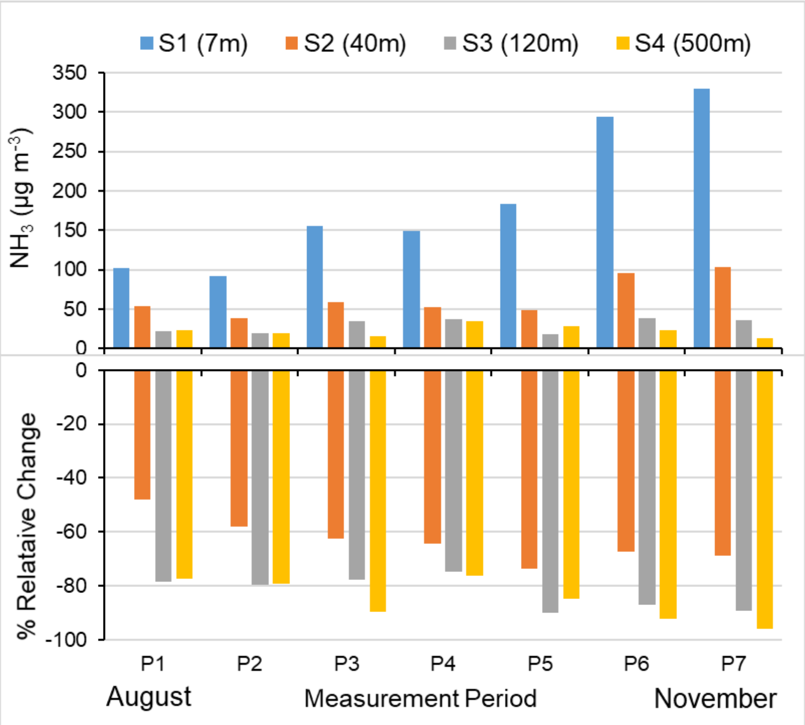


Figure 36 (TOP) Comparing NH_3 concentrations at site 1 (next to poultry housing) with other sites along the downwind transect. (BOTTOM) Relative change in NH_3 concentrations (reference = site 1), showing large reduction in concentrations (> 81 %) at sites 2 – 4 a

Tree growth, leaf morphology and nutrient uptake

At Poultry 4, sampling was carried out at all points under trees where ammonia was also measured (map with transects provided by CEH). Additional points maked with red were added for tree assessments to increase the number of points along the transects. Tree height, diameter and canopy nitrogen uptake were lowest at Poultry 4 farm compared to other farms due to very young age of the trees (Figure 38). Despite the young age of the trees, tree growth in terms of height, diameter and also LAI seems to be higher at 40 m compared to 80 m away from Poultry 4 farm as seen at the other farms. Tree nitrogen canopy uptake ranges between 0.8-1.4 kg N/ha and is similar between 40 and 80 m away from the farm.

At Poultry 3 farm, sampling was carried out at all points under trees where ammonia was also measured (map with transects provided by CEH). Additional points maked with red (Figure 30) were added for tree assessments to increase the number of points along the transects. Tree height and diamater decline with distance away from Poultry 3 farm (Figure 37). Tree height and diameter were highly variable at 10 and 30 m points of the transects as there were fast growing tree species represented at these two points such as Poplars and Willow and not at the 50 and 60m distance. Specific species height and diamater showed higher growth by Poplar which is three times higher than oaks. That is to be expected as oak is a slow growing species.

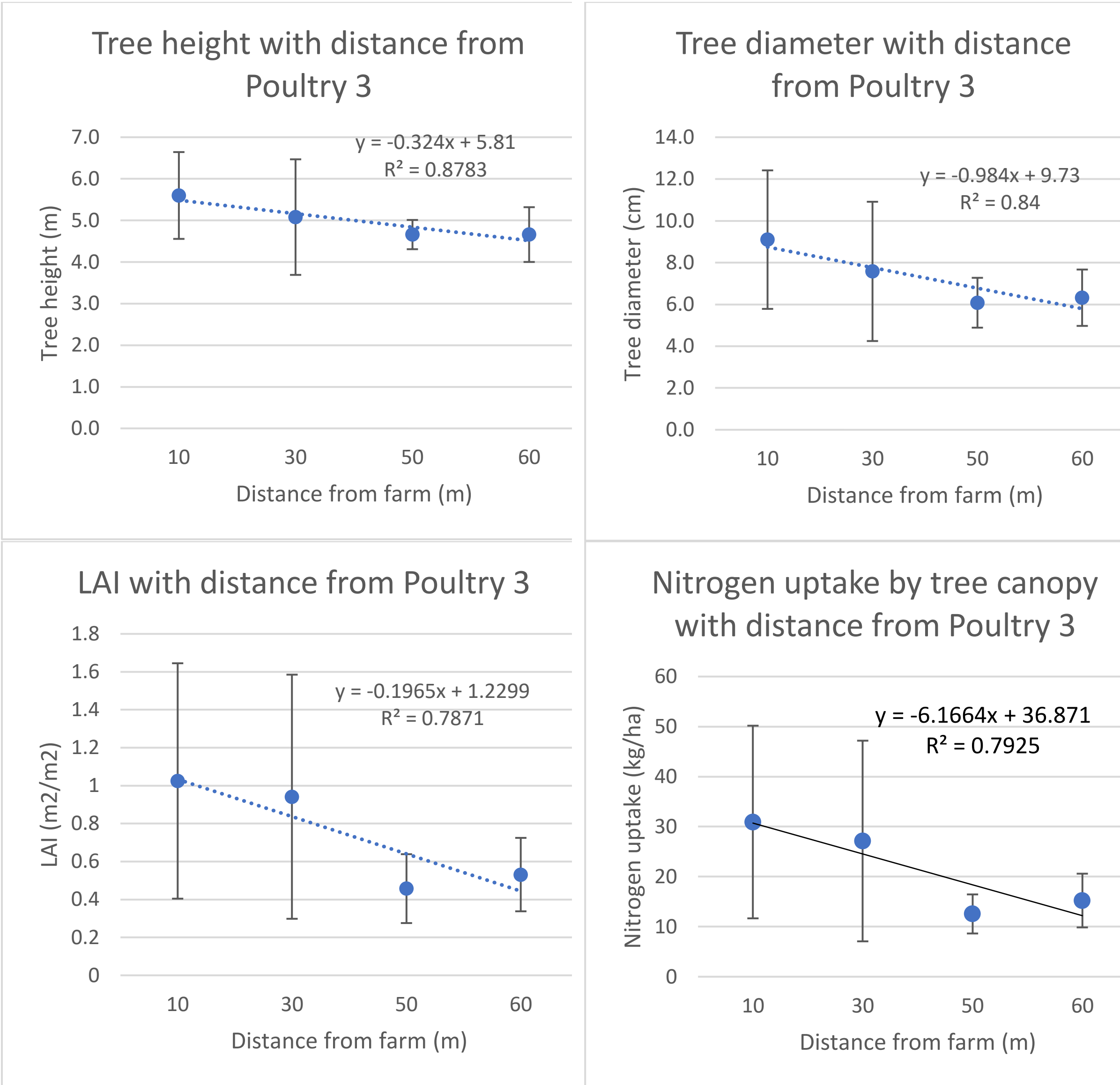


Figure 37: Tree height, diameter and LAI with distance away from Poultry 3 farm. Mean values from 5 trees of different species for each point in Transect 1 and 2 are presented and vertical bars are standard errors of the mean. An indicative linear relationships is drawn between tree parameters and distance from farm.

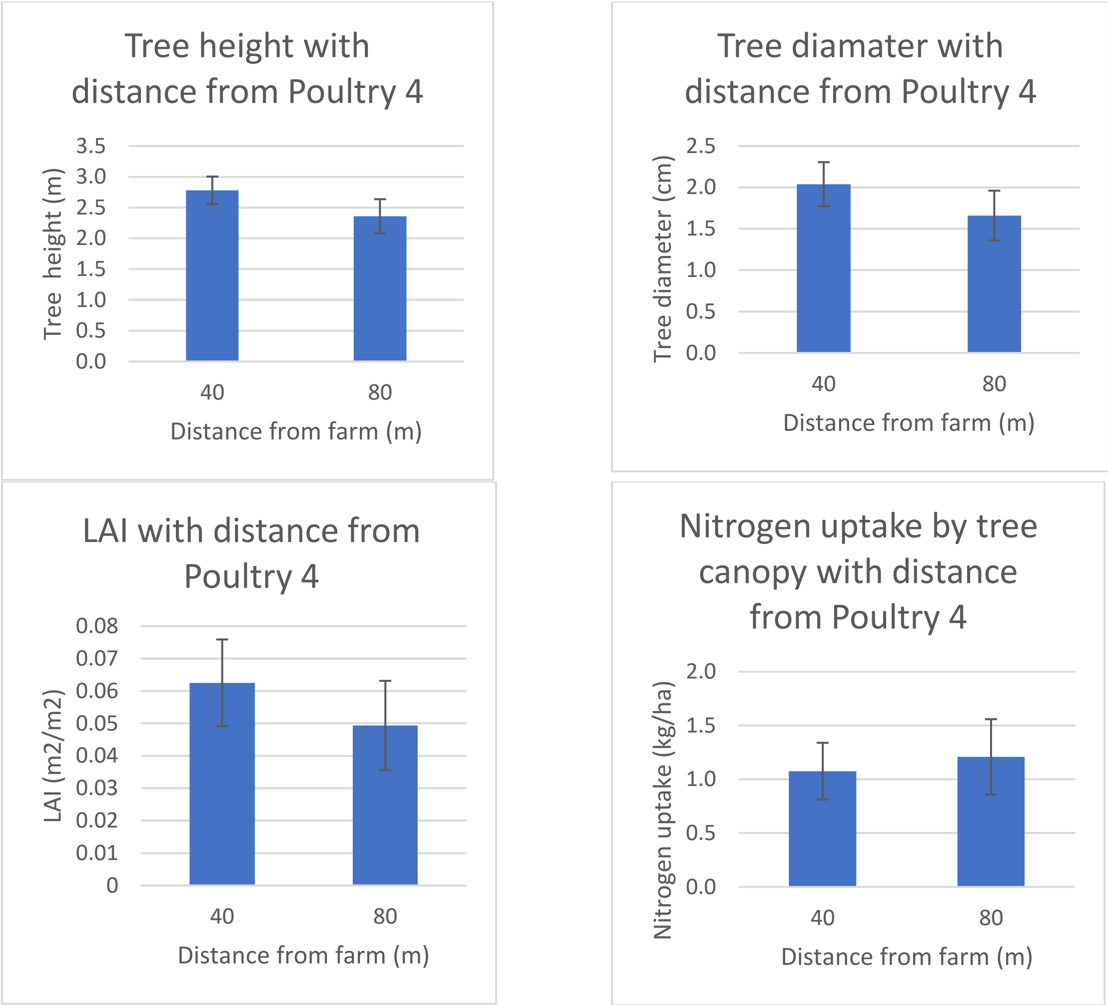


Figure 38: Tree height, diameter and LAI with distance away from Poultry 4 farm. Mean values from 5 trees of different species for each point are presented and vertical bars are standard errors of the mean.

Modelling

The number of ammonia sources (poultry sheds) around Poultry 3 and Poultry 4 make the modelling complex. To improve the correlation between modelling and measurements three periods (out of seven) that had the most consistent wind direction were examined. Periods with west and southwest winds were chosen to match the direction of measurement transects (Table 26). Period 3 had the best consistent west/south-west wind directions over its two week period. The main sources in and around Poultry 3 and Poultry 4 modelled to try and capture the ammonia emissions field for the area. These sources were modelled for all three periods. The sources included the shed at Poultry 4 and Sheds 13,14,19, at Poultry 3 plus the Poultry 3 shed that was under our intensive monitoring study (shed 15 & 16).

Table 25 shows the results of modelling vs measurmetns across two treebelts – one at Poultry 4 (3 to 4) and one at Poultry 3 (6 to 7), also shown in Figure 30. The change in concentrations at Poultry 4 between modelled and measurements showed a steeper decline with the modelled runs for each period. The model result for site 1, the nearest monitoring point to the shed at Poultry 4, was significantly lower when compared to the measurements. The values are less than 1 µg^{-3} which indicated the model is not performing well with very close-by receptor points. A similar experience was seen at Poultry 1 (Section 0). However, for the other before and after treebelt area (site 6 to 7) the change in concentrations was higher with the measurements where for each period a larger reduction in the measreument data compared to the modelled data was seen (1%, 9% and 11%).

Table 25: Modelled (SCAIL) vs measured (ALPHA) for Poultry 3 (Sites 5 to 9) and Poultry 4 (sites 1 to 4) for 3 periods. The green cell shows where a treebelt exists between two sampling points. A positive difference between modelled and measured indicates the change in concentrations are higher in the measured data which could be explained by the presence of a treebelt.

Period	**Sampling Site**	**NH_3 SCAIL**	**ALPHA**	**SCAIL % conc △**	**ALPHA % conc △**	**SCAIL vs ALPHA**
Period 3	1	0.36	156			
Period 3	2	51.16	58.5	69%	41%	**Difference**
Period 3	3	16.03	34.7			**-28%**
Period 3	4	9.96	16			
Period 3	5	26.66	144			
Period 3	6	22.87	97.7	34%	35%	**Difference**
Period 3	7	15.02	63.7			**1%**
Period 3	8	9.37				
Period 3	9	9.41				
Period 3	Bk10	0.41	13.30			
Period 5	1	0.30	182.93			
Period 5	2	24.71	48.30	78%	63%	**Difference**
Period 5	3	5.51	18.01			**-15%**
Period 5	4	8.08	27.96			
Period 5	5	15.89	52.46			
Period 5	6	14.18	40.63	26%	35%	**Difference**
Period 5	7	10.49	26.26			**9%**
Period 5	8	10.15	46.01			
Period 5	9	12.54	59.26			
Period 5	10	0.11	27.18			
Period 7	1	0.27	329.31			
Period 7	2	45.30	102.90	71%	65%	**Difference**
Period 7	3	13.19	35.88			**-6%**
Period 7	4	5.88	13.18			
Period 7	5	20.83	108.18			
Period 7	6	17.85	65.41	28%	39%	**Difference**
Period 7	7	12.84	39.72			**11%**
Period 7	8	10.36	23.92			
Period 7	9	12.28	18.43			
Period 7	Bk10	0.47	8.62			

3.2 Poultry 3 Intensive Experiment

This project and report does not carry out an in-depth analysis of the high resolution data, but it will be prepared for future use. Simple plots and correlations are presented. Two intensive sites were set up Site 1: in front of treebelt, NE of poultry housing (= ALPHA site 5) and Site 2: NE of site 1, on the other side of the 23 m treebelt (= ALPHA site 7) (see Figure 2). The Poultry 3 Intensive experiment had four main components:

1. **Cross calibration of ammonia instruments.**

   To compare AiRRmonia wet-chemistry instruments operated by UKCEH and the Los Gatos automatic NH_3 gas analysers operated by EA, and to advance the development of a suitable calibration protocol with ammonia gas (from a cylinder) for deployment in future studies

2. **High resolution measurements of NH_3 and local meteorology**

   High time resolution allows for visual interpretation of plumes and source apportionment. Data collected can be used for back-trajectory emissions modelling, and to assess differences between the concentrations in front of and after the treebelt. It is important to note that this study is only looking at different concentrations across the treebelt, rather than flux measurements, and data in general should be used in combination with modelling.

3. **High resolution measurements of Methane (CH_4), Carbon Dioxide (CO_2)**

   CH_4 and CO_2 will be used as tracer gases for NH_3 as but they do not interact strongly with surfaces of the landscape (e.g. trees), but are assumed to be diluted in the atmosphere through physical dispersion at the same rate as NH_3. The relative depletion of NH_3 compared to the CH_4/CO_2 can give an indication or quantification local loss.

4. **Directional Passive Ammonia Sampler (DPAS) trial**

   To test an approach for deriving a directional signal from a DPAS in a complex farm environment, and attempt to detect reduction in NH_3 due to capture of NH_3 by trees.

3.2.1 NH_3 calibrations

The AiRRmonia instruments were the primary instrument for measuring NH_3 at high temoral resolution (response time ~15-20 minutes, data recorded every minute), therefore care was taken to ensure both AiRRmonia instruments were operating under well calibrated conditions. The AiRRmonias were calibrated every 2 weeks with aqueous ammonium standard solutions. In addition, two AiRRmonias were operated in parallel over a one week period (final week 8) at site 1. The side-by-side comparison showed excellent agreement between the two AiRRmonia over the range of NH_3 concentrations measured of between < 0.1 to > 300 μm^{-3} (Figure 39). In addition an ammonia gas cylinder standard was used for gas phase calibrations producing slopes of 0.93 and 0.90, respectively (Figure 39). Since the field calibration is a long process and there was limited time available on site, a ~30-60 minutes stabilisation period was used between different gas phase concentrations. Given the relatively short stabilisation period, there is confidence the AiRRmonias are quantifying the gas phase NH_3 concentrations to an acceptable level. An extended calibration was also undertaken with the calibration solutions up to high concentrations post-field campaign to check for non-linearities at the very high concentrations measured at Poultry 3. A small baseline offset (~10 µg m^{-3}) was found in the gas phase calibration. However, given the uncertainty in the calibrations, this correction has not been applied to the AiRRmonia data, since the calibration curve applied in the field was found to be acceptable.

Also at the intensive sites were two LGR NH_3 instruments therefore measurements were made in parallel. The 1-minute high resolution data from one pair of instruments are compared in Figure 40. As can be seen in Figure 41 there was a correlation between the two instruments but a significant difference (around double) in the LGR NH_3 concentration which is thought to be due to internal contamination.

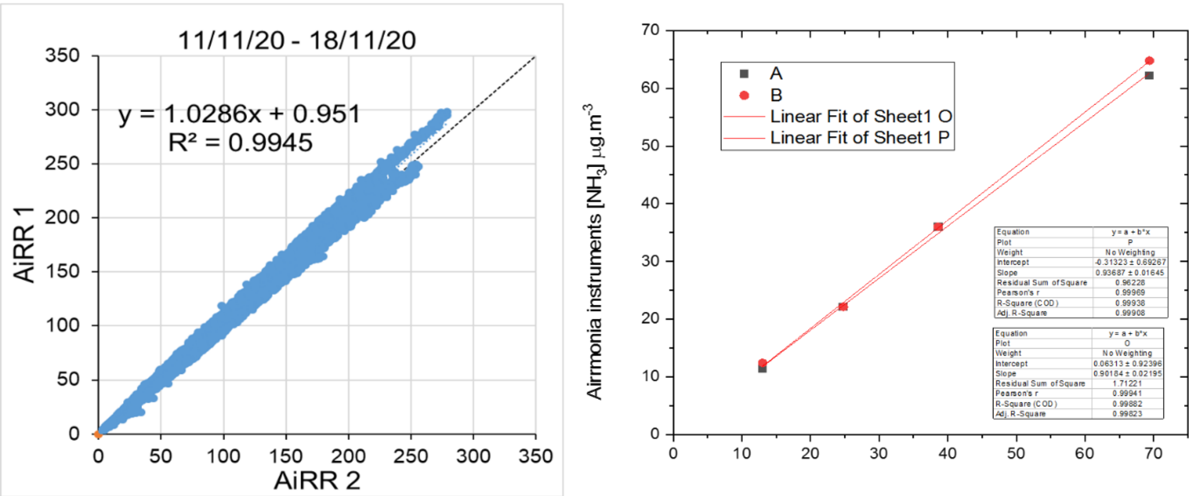


Figure 39 AiRRmonia instrument side by side comparison (LHS) and gas standard calibration (RHS)

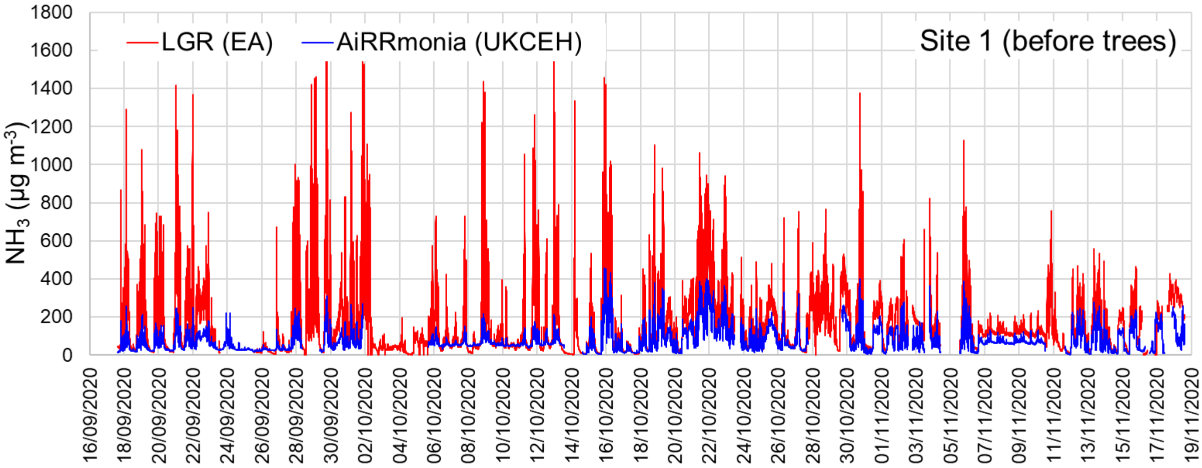


Figure 40: Time series plot comparing high resolution NH_3 measurements on the LGR (EA) and on the AiRRmonia. The LGR NH_3 data appears to read higher than the AiRRmonia.

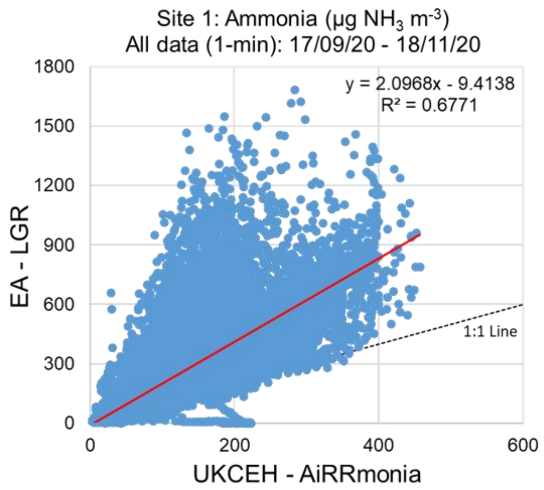


Figure 41 Regression analysis of NH_3 measurements by the LGR vs AiRRmonia for two periods.

3.2.2 Summary of high resolution data

High resolution NH_3, SO_2, CH_4, PM and met. data are summarised in Figure 42.

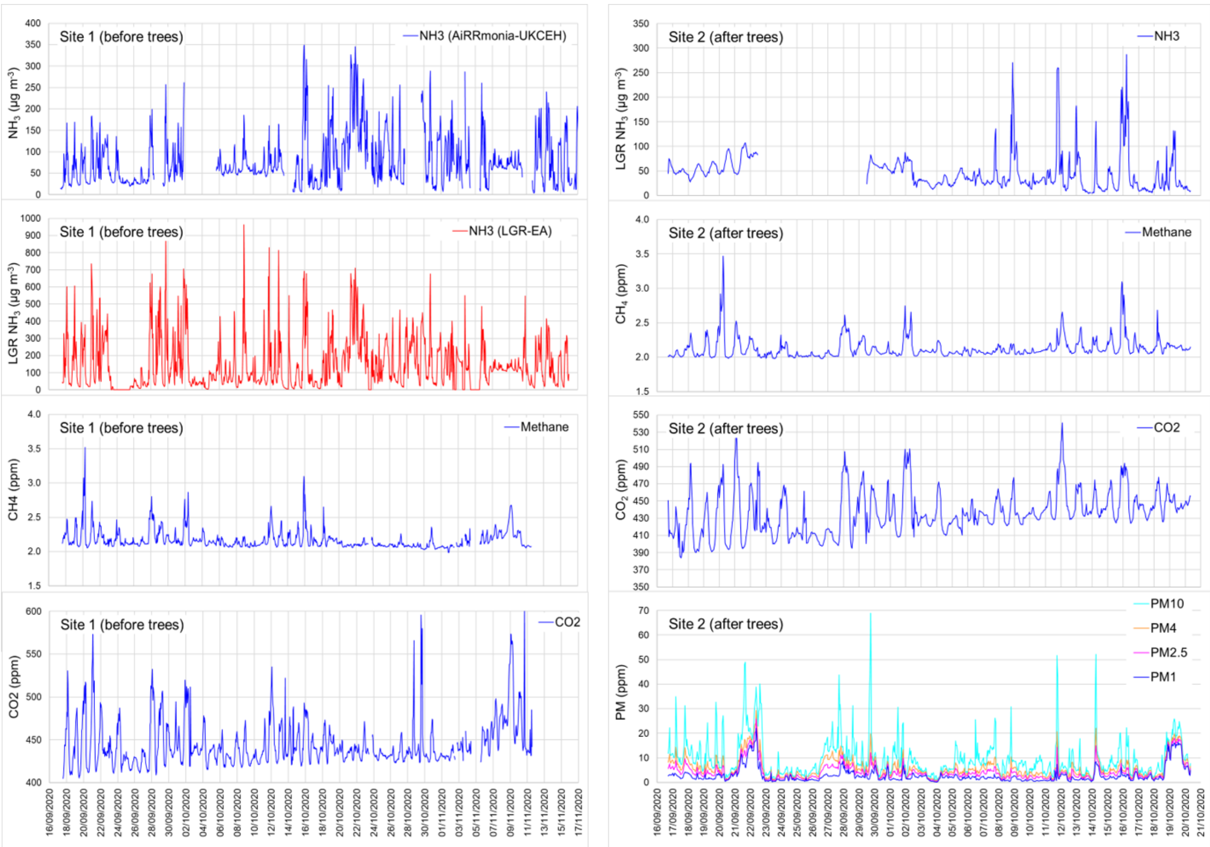
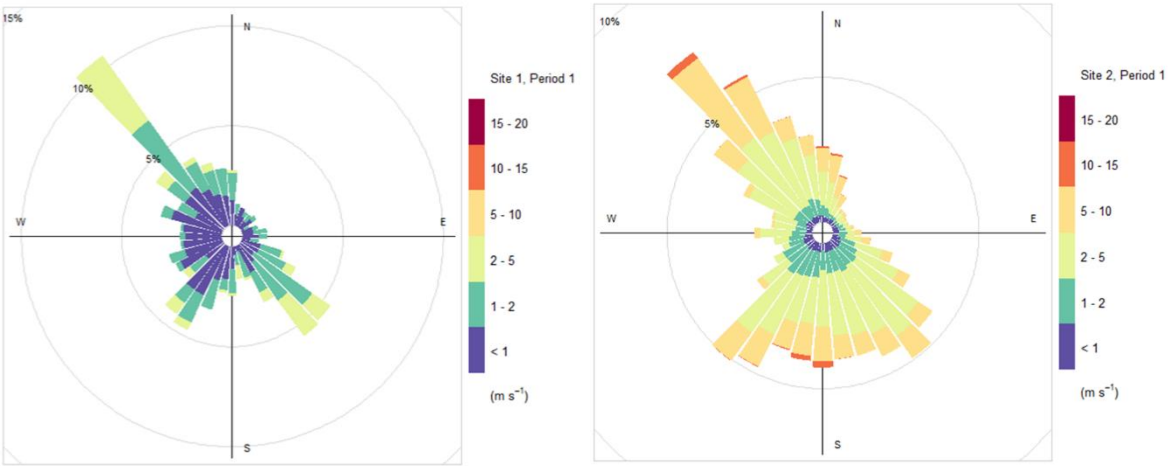


Figure 42 Time series plot of high resolution NH_3 (AiRRmonia and LGR), CH_4, CO_2 and PM data (aggregated to hourly values from 1-minute data.) at site 1 in front of the tree treebelt at Poultry 3. The baseline in CO_2 and CH_4 appears to be drifting upwards in time as per the natural seasonal cycle.



Site 1 AiRRmonia NH_3 **Site 2 AiRRmonia NH_3**

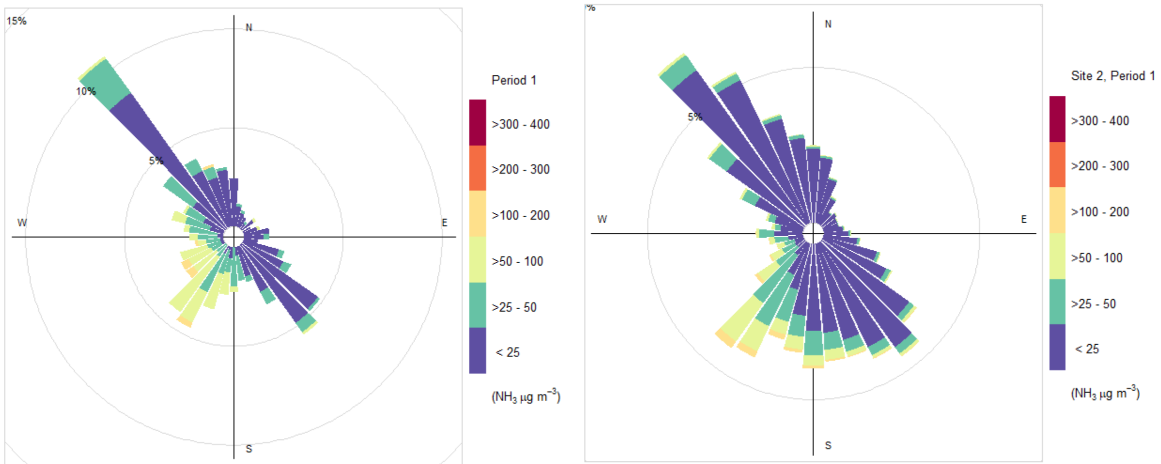


Figure 43: Wind rose and ammonia (AiRRmonia data) polar plots for (LEFT) Site 1 weather station at site 1 before trees (height = 2 m), and (RIGHT) Site 2 weather station at site 2 behind trees (height ~8m). This shows different wind profiles at the two locations, likely due to difference in monitoring height. The highest NH_3 concentrations are from the directions of the poultry shed and ranging area.

Diurnal plots for NH_3 (AiRRmonia data), CH_4, CO_2 and PM (PM_1, $PM_{2.5}$, PM_4, PM_{10}) made at site 2 are summarised in Figure 44. Diurnal plots in hourly aggregated mean NH_3 (AiRRmonia), CH_4 and CO_2 concentrations at site 1 ran over the period 16/09/2020 to 18/11/2020 and at site 2 ran for 5 weeks, from 16th September to 20th October 2020. A strong diurnal cycle is observed in the NH_3 data from both the LGR and AiRRmonia, and at both sites 1 and 2. Lowest 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. The high resolution (raw) data for the AiRRmonia instrument is shown in Figure 42 (top plots) in front of (site 1) and after the treebelt (site 2).

3.2.3 Diurnal cycles

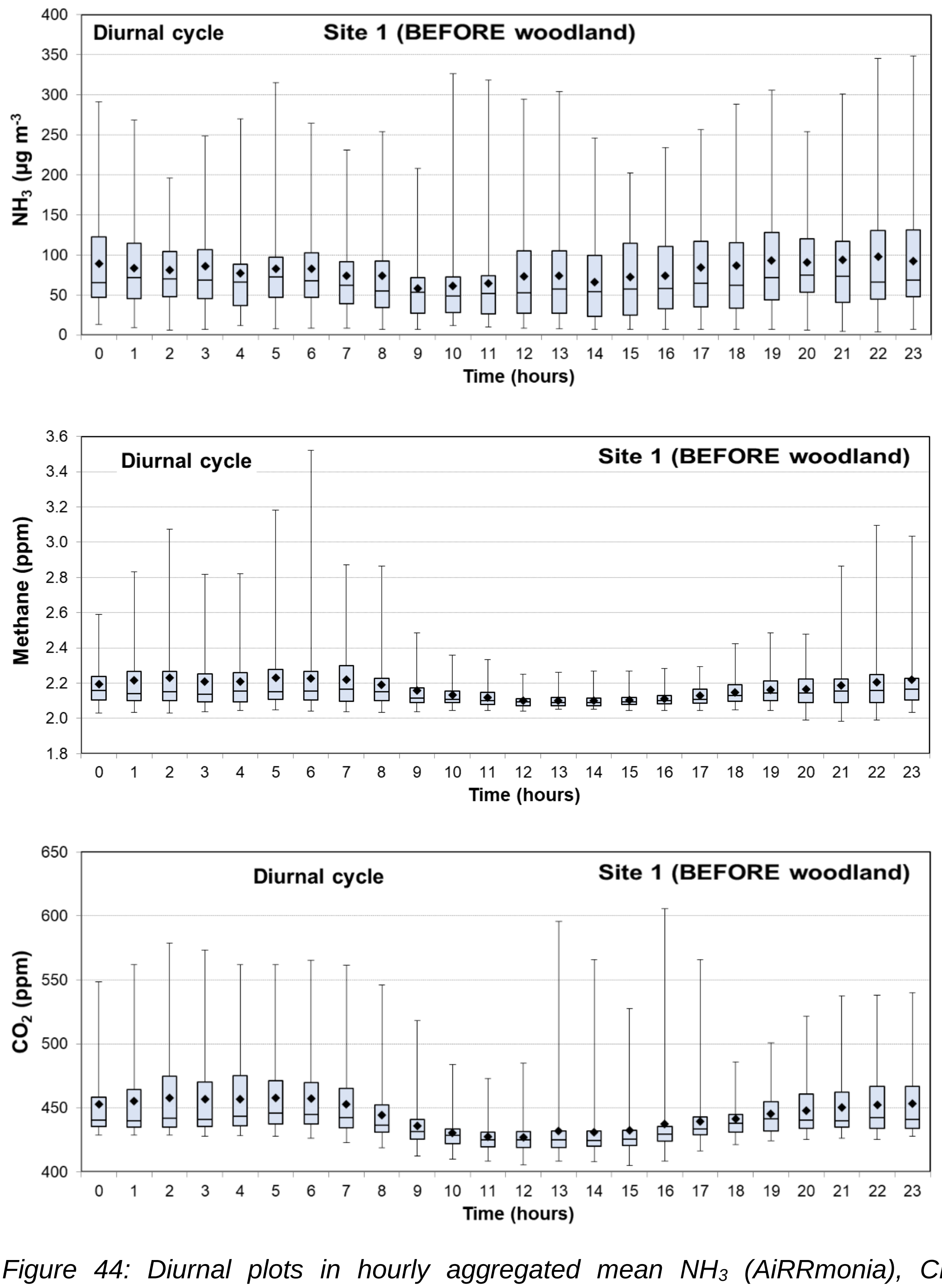


Figure 44: Diurnal plots in hourly aggregated mean NH_3 (AiRRmonia), CH_4 and CO_2 concentrations at site 1 over the period 16/09/2020 to 18/11/2020. This shows a strong diurnal pattern, with smallest concentrations during the daytime when chickens are ranging outside and highest during the night-time when chickens are back inside the housing and emissions occur from the single shed from the vents.

3.2.4 Using CH_4 and CO_2 to estimate relative depletion of NH_3

NH_3 has a shorter atmospheric lifetime compared to CO_2 and CH_4. 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 may 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. The dispersion of the different gases are similar in winds of > 0.2 m s^{-1} (Ko et al. 2018 and references therein). The concentrations of CH_4 was observed to be correlated with CO_2 ($R^2 > 0.5$, Figure 44). At night-time, the maximum concentrations in CO_2 and CH_4 (Figure 44) may be related to plume from poultry shed containing CO_2 respired by the chickens and CH_4 formed from decomposing poultry litter (methanogenesis). The peak periods in CO_2 and CH_4 concentrations coincides with maximum concentrations of NH_3. Using the one minute meteorological data from site 2 (EA van, measuring wind direction (WD) and wind speed (WS) above the trees, NH_3 from the AiRRmonia, CH_4 and CO_2, a fractional depletion due to uptake of NH_3 by the trees was 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).

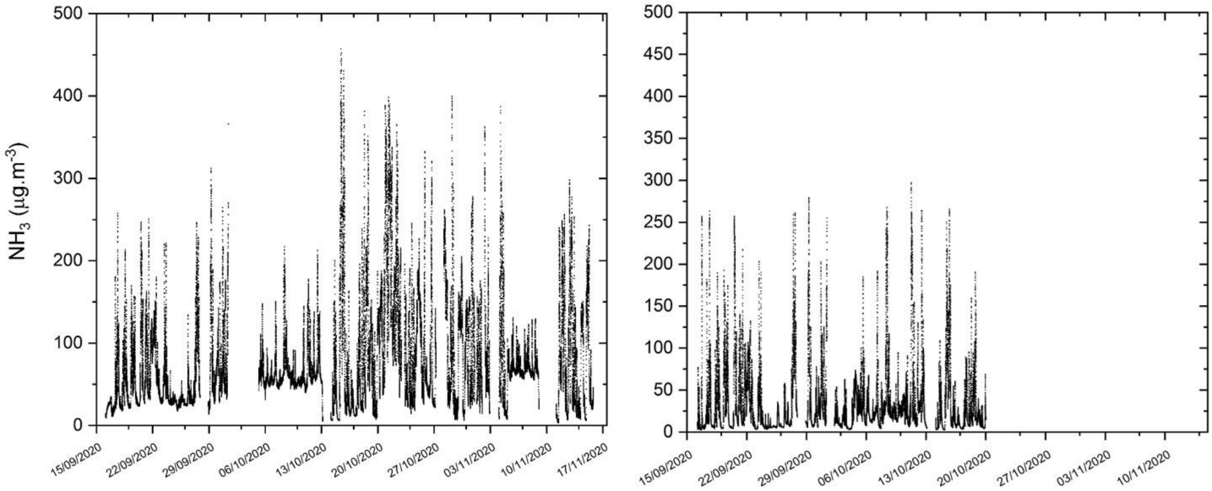


Figure 45 AiRRmonia NH_3 concentrations (1-min data) measured at site 1 before treebelt (LHS) and at site 2 after trees belt (RHS)

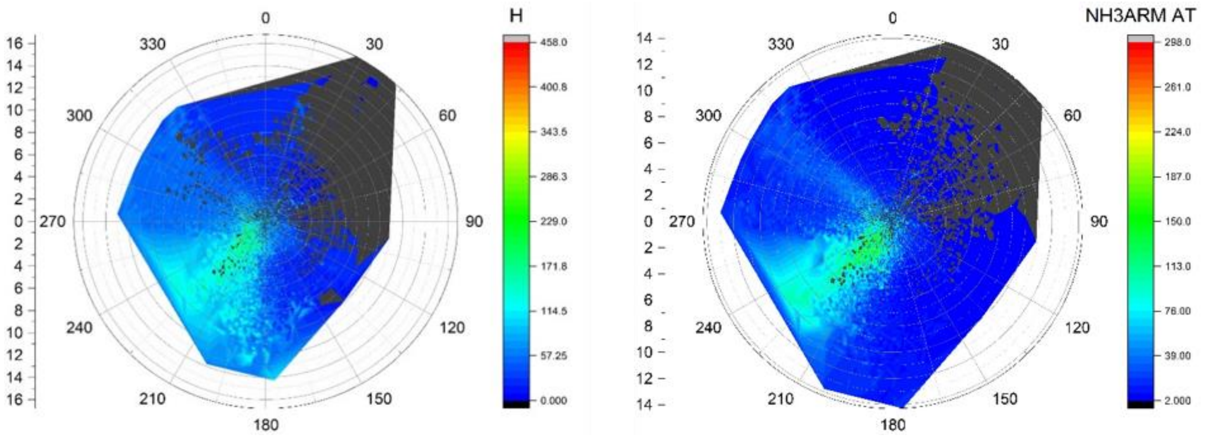


Figure 46 Wind direction wind speed polar plot of NH_3 concentration before trees (LHS) and after trees (RHS)

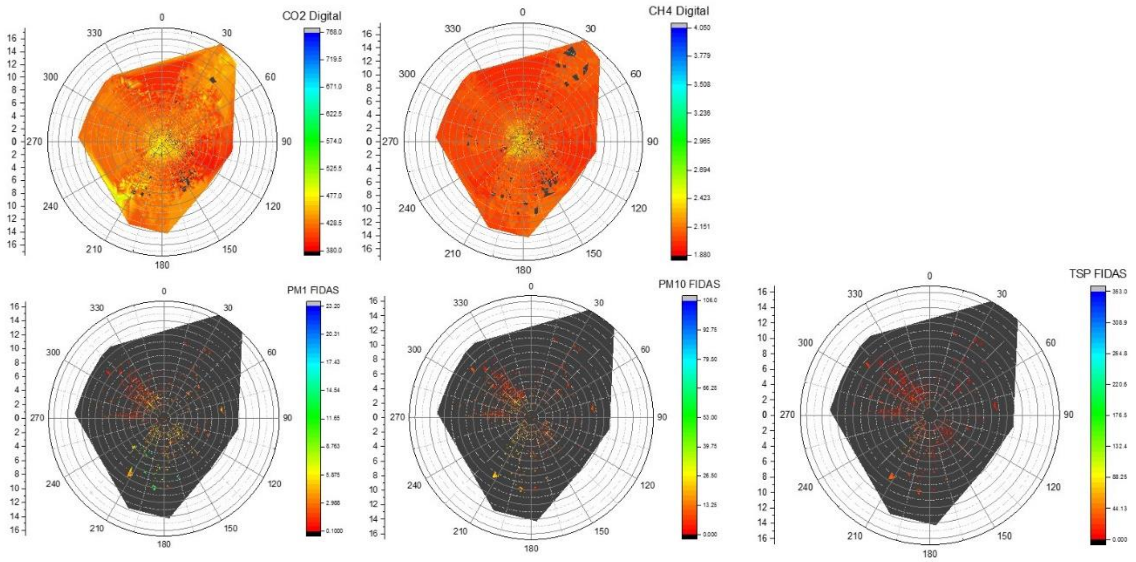


Figure 47: CO_2, CH_4 and as a function of wind direction and wind speed on far side of trees.

An estimate of the depletion of NH_3 due to recapture can be obtained by considering the ratio, *f*, where:

$$f = \frac{\left(\left([NH_3](S2) - [NH_3](S1)\right)/ENH_3\right.}{\dfrac{[CO_2]\,(S2) - [CO_2]\ \,(S1)}{E[CO_2]}}$$

Where:

NH_3 is concentration (µg m^{-3}) at Site 2 (S2) and Site 1 (S1)

CO_2 is concentration (µg m^{-3}) at Site 2 (S2) and Site 1 (S1)

E is emission (µg s^{-1})

It is assumed that there will be minimal deposition of CO_2 to the treebelt compared with NH_3. If deposition of NH_3 is greater than CO_2, this will result in a decrease of the ratio of air concentrations of NH_3 to that of CO_2, and the value of *r* will be less than 1

Table 26: Fractional loss due to tree uptake of NH_3 (first draft calculation)

	N total	*f*
NH_3 loss relative to CH_4	1969	0.0033
NH_3 loss relative to CO_2	1969	0.0686

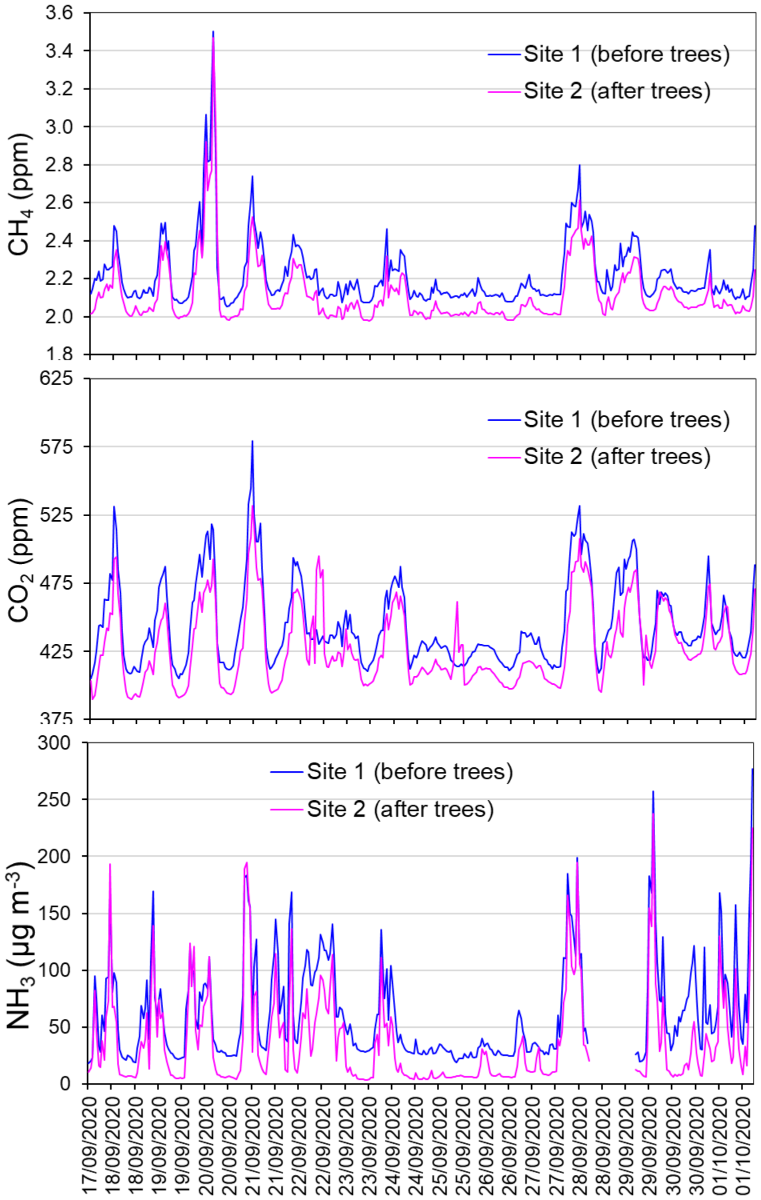


Figure 48: [CH_4], [CO_2] and [NH_3] profile downwind of poultry housing, before and after treebelt.

3.2.5 DPAS-MANDE

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. Subsequent DPAS-MANDE work was focused on “screened in” data for periods and sectors when the wind speed and duration were moderate or greater. Improvements to the DPAS have been proposed to resolve the alignment issue in future.

Comparison of DPAS and automatic monitoring data

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 µg/m^3 from DPAS and automatic data, respectively. A similar comparison for 9 sectors/periods using modelled winds gave average concentrations of 39.6 and 36.9 µg/m^3 from DPAS and automatic data, respectively. Another comparison showed that DPAS and automatic data agreed within ~5% for concentrations averaged over 1-4 sectors and 2 weeks.

Reductions in ammonia by trees along transects at the 6000-bird shed

Reductions in ammonia fluxes and concentrations and fluxes were evaluated between the **before trees** and **after trees** positions of DPAS-MANDEs at the 6000-bird shed. The percentage reductions were similar for fluxes and concentrations, and were based on screened-in data for 30° sectors averaged over 4-6 weeks. The percentage reductions in fluxes for specific transects were (Figure 49):

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

The lower rate of reduction for the shed airflows compared to the ranging area airflows, 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.

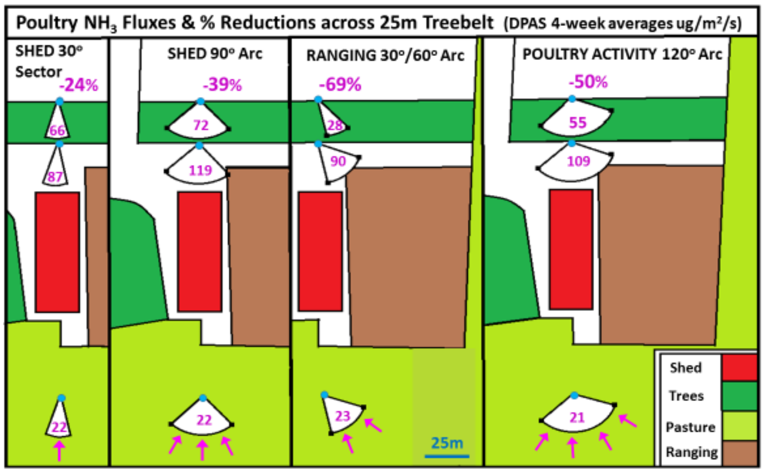


Figure 49: Poultry ammonia fluxes (µg/m2/s) and percentage reductions across 25m of trees for 4 transects at the 6000-bird shed: 4-week-averages for individual and combined 30o sectors from DPAS sampling

Detection of ammonia from neighbouring poultry farm

The **upwind** DPAS-MANDE detected an ammonia plume from a neighbouring poultry farm that was ~0.5km upwind (prevailing) from the intensive measurements farm. This detection was shown by the fact that the ammonia flux from a 30° sector containing the neighbouring farm was about 80% more than from adjoining sectors containing only pasture and background levels of ammonia (Figure 50). There was a treebelt at the neighbouring farm that would have partly abated the ammonia emissions from that farm. The fact that the DPAS-MANDE system could detect such a distant ammonia source, despite an intervening tree belt, suggests that the system is useful for surveying landscape ammonia.

Reduction of background ammonia by trees.

Ammonia concentrations and fluxes were monitored in a 30° sector of well-mixed background air that approached one side of the intensive measurements farm from fields of sheep pasture. The air from half of the sector passed obliquely through 65 m of the treebelt, and the DPAS-MANDE data indicated that its ammonia flux was reduced by ~25% over this distance (Figure 51). This implied that the flux would have been reduced by ~50% if all of the air in the sector had passed through the trees. These reductions could be attributed solely to interception by trees, with no contribution from plume dispersion; this was because the ammonia in the background air was well-mixed and not part of a dispersing local plume. By contrast, the reductions in ammonia along other transects at the intensive

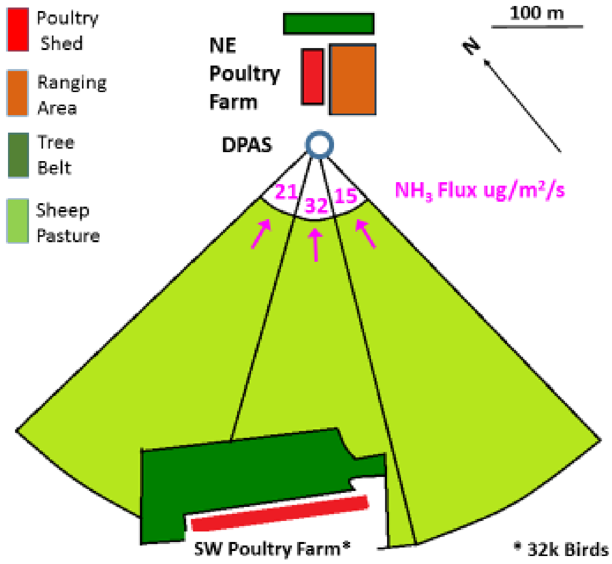


Figure 50: Ammonia fluxes from neighbouring poultry farm measured at "Upwind" DPAS (4-wk averages)

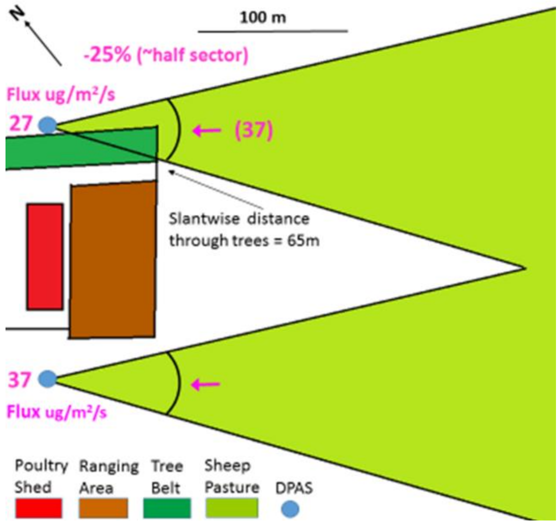


Figure 51: Ammonia flux in well-mixed background air from sectors containing sheep pasture, showing partial interception and reduction (-25%) by trees (top):6-week-average of DPAS monitoring, µg/m2/s.

measurements farm included contributions from dispersion of plumes from local poultry activities, as well as from interception by trees.

Comparison of ammonia reductions based on measured and modelled winds
Ammonia concentrations and fluxes were evaluated separately for 2 sources of wind data:

1. on-site measurements and

2. modelling based on Numerical Weather Prediction (NWP).

The NWP data were for a reference height of 10 m, and it was necessary to decelerate them so that they matched the measured wind speed, which was at a height of 2.3 m. Although the NWP-based wind speeds were decelerated, the amounts of time during which NWP-based winds blew from each 30° sector were not adjusted. After decelerating the NWP wind speeds, the amounts of ammonia reduction by trees based on NWP data were comparable to those based on measured wind data. This suggests that in future it may be feasible to evaluate DPAS samples using NWP data (i.e. without having to make wind measurements), which would simplify fieldwork.

Reduction in ammonia concentrations (/fluxes)

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-belt width of 25m – noting that the ammonia reduction is not necessarily linear with depth of treebelt. The lowest normalised reduction was about 20% for the background transect, and the highest was ~60% for the ranging area (Table 27). 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 27: Percentage reductions by trees in NH_3 fluxes & concentrations: summary for different transects showing emission height, distance through trees and reductions normalised to 25m (4-6wk 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.

3.3 Multi-Farm Results

3.3.1 Species effects of tree growth, leaf morphology and nutrient uptake

Averaged tree parameters for all farms are reported in Table 28 as trees were of similar age (with an exception of Poultry 4) and similar climate. The number, and list of tree species measured for each farm are listed in Table 29. The tree species specific parameters are reported in Figure 52 to Figure 55. 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 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 varried greatly with tree species, with the average range of 0.1 for hawthorn to 2.5 m^2 m^{-2} for Poplar. These LAI calculated from measured data are for young trees which will differ when trees mature. For example LAI of mature birch will be lower than Oak and Sycamore as birch has very light canopy. Mature Oak also has higher LAI than Ash which is not the case in the young trees at the farms treebelts. 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 compared to other species where nitrogen uptake was <20 kg N/ha. Variability in tree growth of different species is due to differences in species ages at the different farms, but also potential difference in soil type and nitrogen supply to trees.

Table 28: Average and variabilities of tree parameters – diameter at breast height, height, Leaf Area Index and canopy nitrogen uptake (standard deviation, standard errors and number of trees assessed) at Poultry 1, Poultry 2, Poultry 3, Poultry 4 and Dairy 1 & 2 tree treebelts farms.

Site	Tree	Diameter	Height	LAI	Nitrogen uptake
		cm	m	m2/m2	kg N/ha
Poultry 1	average	7.52	5.04	0.79	21.66
	sd	4.80	2.22	0.82	21.28
	se	0.72	0.33	0.12	3.17
	number	45	45	45	45
Poultry 2	average	9.66	5.66	0.45	25.28
	sd	4.65	1.86	0.47	21.54
	se	0.63	0.25	0.07	3.14
	number	45	45	45	45
Poultry 3	average	8.44	5.36	0.95	26.64
	sd	5.68	2.04	1.15	32.29
	se	1.04	0.37	0.23	6.46
	number	25	25	25	25
Dairy 2	average	1.85	2.57	0.06	1.14
	sd	0.58	0.53	0.03	0.66
	se	0.17	0.15	0.01	0.21
	number	10	10	10	10
Dairy 1	average	10.91	6.11	0.83	20.11
	sd	5.59	2.47	0.69	17.51
	se	1.12	0.49	0.14	3.50
	number	25	25	25	25

Table 29: Numbers and list of tree species assessed at the farms.

Number	Poultry 1	Poultry 2	Poultry 3	Dairy 2	Dairy 1
24	Ash	Ash			Ash
25	Birch	Birch	Birch		Birch
3	Haw	Haw			
15	Hazel	Hazel			Hazel
2		Norway spruce			
15		Oak	Oak	Oak	Oak
10	Poplar	Poplar	Poplar		
16	Rowan	Rowan	Rowan	Rowan	Rowan
4		Elm	Elm	Elm	Elm
17	G/WILL, C/Will	Willow	G/WILL	G/WILL	Willow
3			Sycamore	Sycamore	
2	Scots pine				
1		Beech			
2		Horse Chestnut			

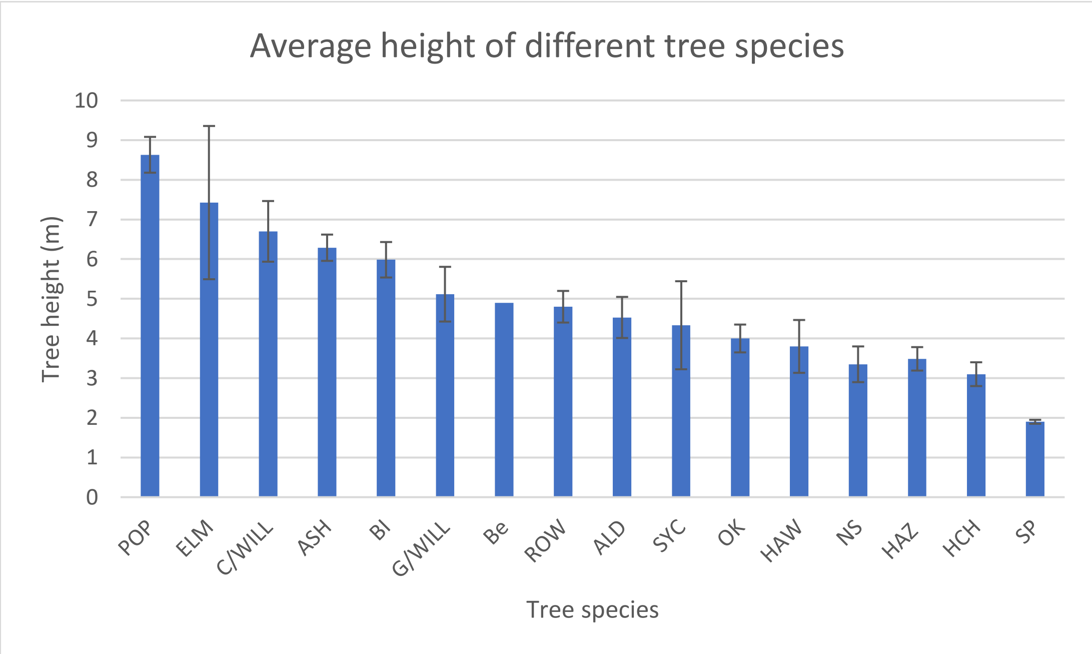


Figure 52: Tree height for different tree species measured across all farms. Bars are mean values for height for each species measured from all sites and vertical lines are standard errors of the mean. Number of tree species are listed in Table 29.

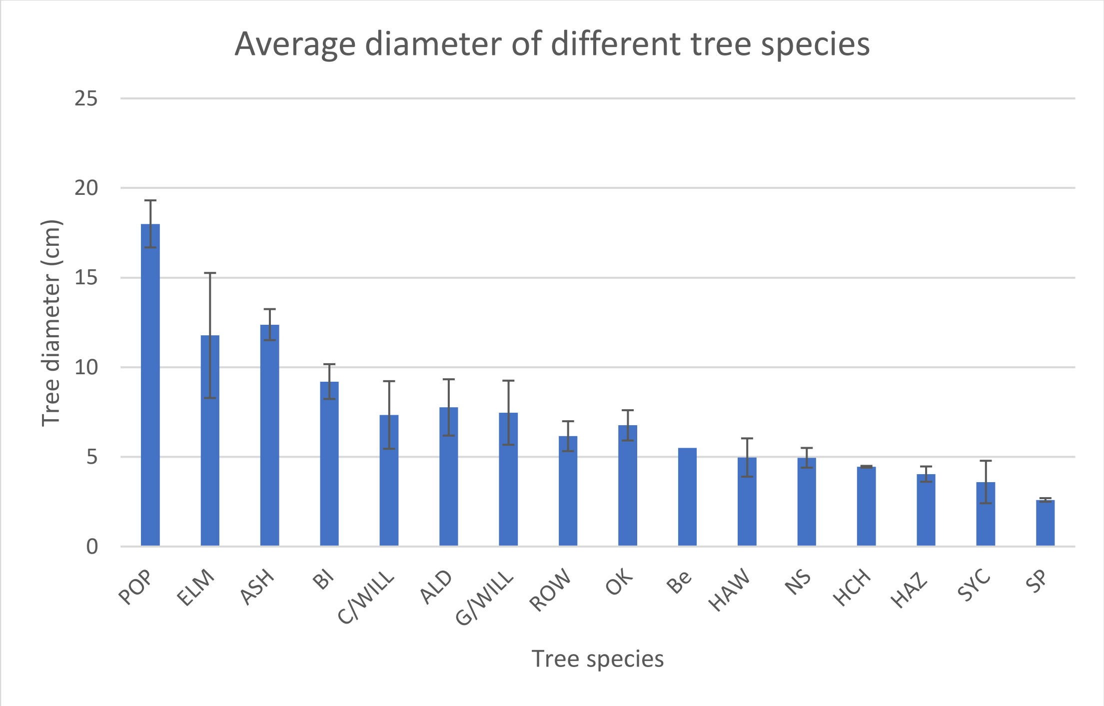


Figure 53: Tree diameter for different tree species measured across all farms. Bars are mean values for diameter at breast height for each species measured from all sites and vertical lines are standard errors of the mean.

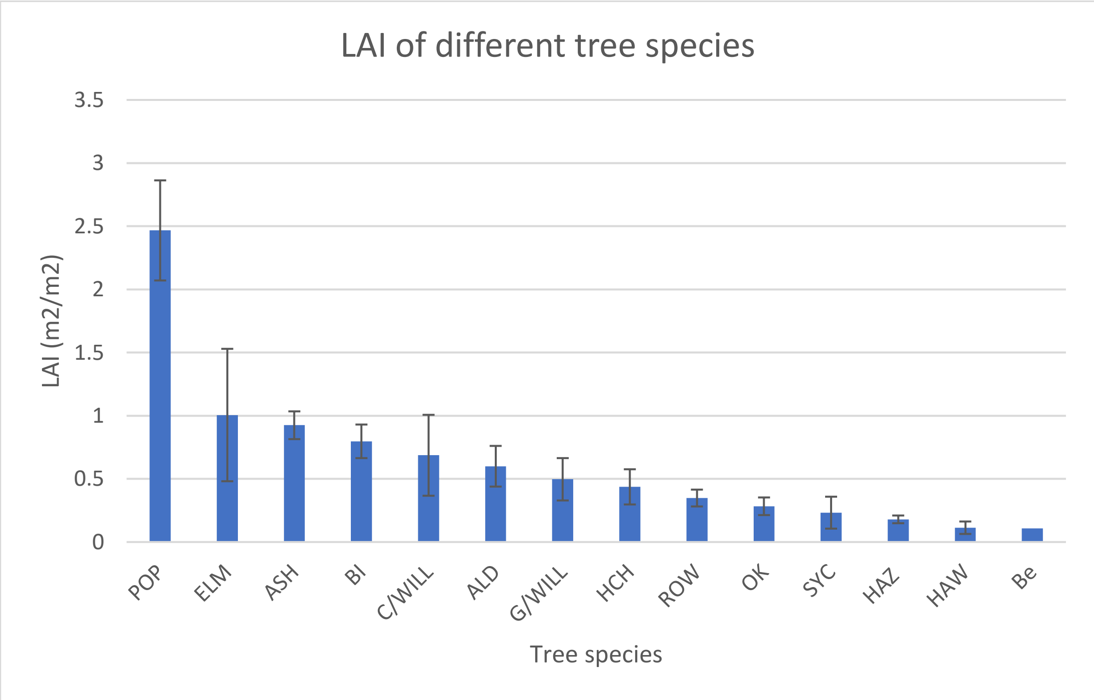


Figure 54: Leaf Area Index (LAI) for different tree species measured across all farms. Bars are mean values for LAI for each species measured from all sites and vertical lines are standard errors of the mean.

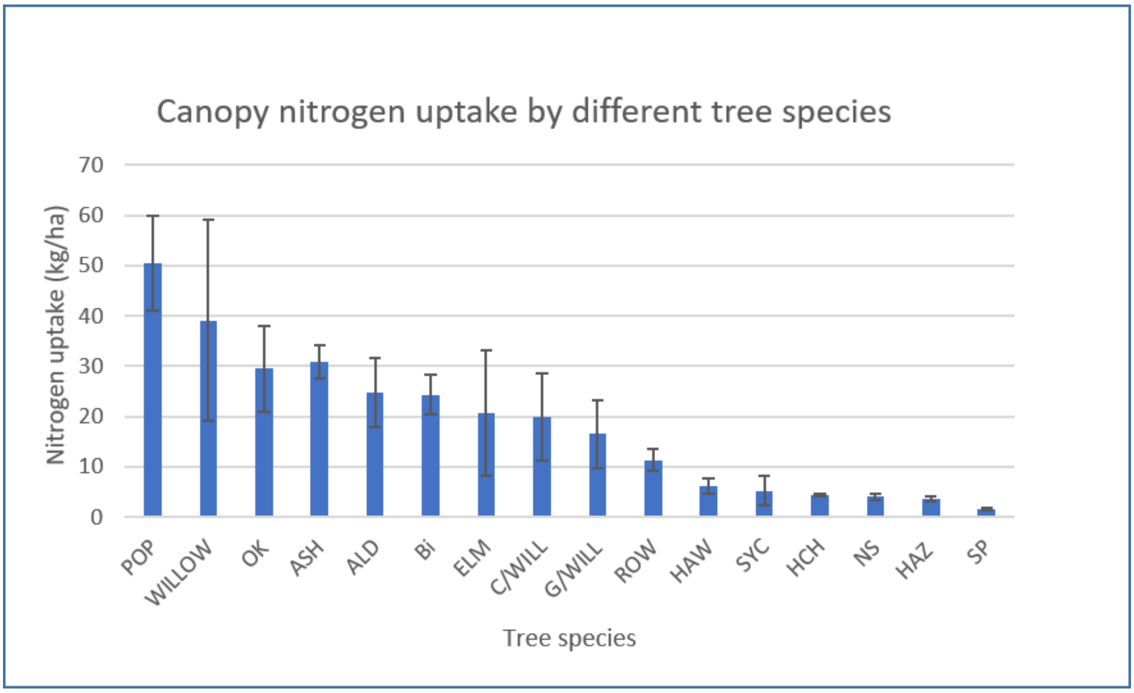


Figure 55 Canopy nitrogen uptake by different tree species measured across all farms. Bars are mean values for canopy nitrogen uptake for each species measured from all sites and vertical lines are standard errors of the mean.

3.3.2 MODDAS-OpenFoam treebelt model

Table 30 shows the sources and treebelts that were modelled. For Poultry 1 and Dairy 2 two runs were carried out to capture differences in emissions and source/shed, lengths, areas and treebelt depths.

Table 31 shows the inputs and results from the model runs. For the input data, LAI and height of the treebelts 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 is 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).

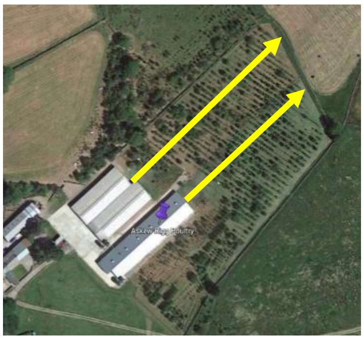
LAI, height and treebelt depth are key determinants for ammonia capture and in the case of Dairy 2 a high (estimated) LAI and height and deep canopy results in a very high capture of 80%. Short treebelts e.g. at Poultry 3 (23 m) give rise to low % capture, although the LAI at Poultry 3 was the highest in the group of farm planted treebelts. The treebelt canopy at Dairy 2 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 height of trees was less than 3 m in height and had an associated very low LAI (0.06) the ammonia capture is negligible.

As trees grow they gain height and subsequently increase their canopy and LAI which gives 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 with reducing the NH_3 emission to the atmosphere in mind either via dispersion or recapture.

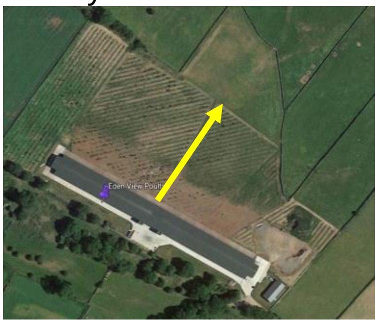
Table 30: Modelled treebelts at each farm showing direction from source to end of treebelt

Poultry 2

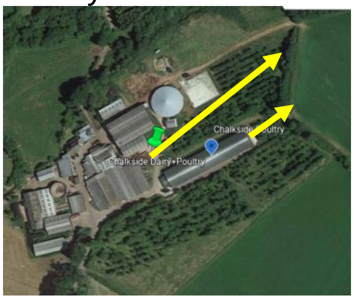
Poultry 3



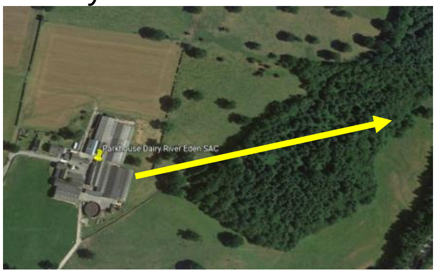
Poultry 1



Poultry 4



Dairy 1



Dairy 2

Table 31: Moddas-OpenFoam results for 8 tree treebelts across 5 farms

INPUT DATA	**Poultry 1 (Fans)**	**Poultry 1**	**Dairy 1 Dairy**	**Dairy 1 Poultry**	**Dairy 2**	**Poultry 2**	**Poultry 3**	**Poultry 4**
Emission Strength (NH_3 tonnes per year)	3480	4060	10366	4640	7774	3480	1740	9280
Height of shed (m)	5	3.6	4	3.6	4	3.6	3.6	3.6
Length of shed (m)	80	50	45	100	50	80	65	20
Area of Shed (m^2)	1630	1800	1350	2000	5836	1772	1270	4400
Distance from shed to main canopy (metres)	25	15	40	7	36	35	26	45
Main canopy depth (m)	100	137	170	36	330	33	23	65
Main Canopy Height (m)	5.04	5.04	6.11	6.11	16.1	5.66	5.36	2.57
Main Canopy LAI (From FR - except. Dairy 2)	0.79	0.79	0.83	0.83	3.10	0.45	0.95	0.06
Backstop (m)	0	0	0	0	0	0	0	0
RESULTS								
Main_recapture	-1.0	-1.6	-4.2	-2.8	-80.6	-1.3	-1.7	-0.1
Back_recapture	0	0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	**-1.0**	**-1.6**	**-4.2**	**-2.8**	**-80.6**	**-1.3**	**-1.7**	**-0.1**

4 Discussion and Conclusions

In order to build confidence in using trees as a means to recapture NH_3 emitted by animal housing on the farm, confidence in measurement methods in real scenarios needs to be built. Over the length of the project we have undertaken over 400 individual ammonia concentration samples (ALPHAS and DPAS), over 150 individual tree samples of foliar N and tree metrics, 20 individual tree assessments for N indicator lichens at two farms, two months of intensive measurements of NH_3, CO_2 and CH_4, and several modelling exercises to understand the evidence of tree effects on ammonia from agricultural sources.

Across these experiments it can be shown that the trees are having 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 treebelts strategically planted in the landscape can mitigate NH_3 concentrations locally to protect sensitive semi-natural sites downwind of livestock housing, plus take some emitted NH_3 out of the atmosphere though recapture. This, in conjunction with other benefits, means that ammonia recapture by trees is part of the toolkit of solutions for reducing N pollution.

Key outputs from the ammonia monitoring (ALPHAS) were seen at Poultry 2 and 3, where an open transect could be compared with a wooded one (Table 32). In these cases a significant difference was observed comparing the data across 5 to 6 two weekly monitoring periods at each farm – Poultry 2 (98%; $p<0.02$) and Poultry 3 (99%; $p<0.01$). Similarly, at Dairy 1, although not a ‘side by side’ comparison, NH_3 concentrations at one sampling site (mean = 18 µg m^{-3}) were on average 16.6% smaller than at a site where there was a gap in tree treebelt, (mean = 21.5 µg m^{-3}).

Table 32: Significant difference tests between open and wooded transect points of same distance from source at two poultry sheds.

	Poultry 2	**Poultry 3**
Treebelt transect	12.4 (*n* = 5)	26.82 (*n* = 6)
Open transect	13.6 (*n* = 5)	33.11 (*n* = 6)
Paired T-Test	P = 0.02	P = 0.01

The two summary tables below show the other key outputs from the concentration measurements and modelling activities. Table 33 shows the average change in concentrations of NH_3 across the treebelts at each farm where modelling was carried out. In every farm, except Poultry 4, the modelled change in concentrations were lower than the measurements indicating a tree effect of some deposition (recapture) and increased dispersion resulting in lower concentrations at the rear of the treebelt. The difference between modelled and measurements ranged from 7 to 14% across the farms (excluding Poultry 4). At Poultry 3 where three measurement methods were carried out including high resolution measurements, similar % changes across the treebelt was shown. Although this varied when looking at individual measurement periods (fortnightly). The difference between modelled and measurements at Poultry 3 was 13% indicating a treebelt effect on the NH_3 plume as it passes through and over the treebelt.

Table 33: Average % change in NH_3 concentration for farm treebelts comparing four methods. The average values are based on the measuring periods at each farm. The modelled values from SCAIL represent the change in NH_3 concentration as if no treebelts are present.

	average % NH_3 concentration difference across treebelt				
Farm / Method	**Poultry 1**	**Dairy 2**	**Poultry 2**	**Poultry 4**	**Poultry 3**
ALPHA	97%	73%	58%	56%	42%
SCAIL (model)	83%ǂ	66%	46%	78%	29%*ǂ
High resolution measurement NH_3					45%**
DPAS					41%**

ǂ SCAIL modelling at these farms did not align well with the nearest sampling point to source. The model was around x10 less than the measurements (discussed in main text); * modelled over 3 measurement periods;** Sept-Oct only

The split between deposition to the canopy and dispersion by the canopy is hard to determine, but if the tracer gas measurements (Table 34) and the % change in concertation at Poultry 3 (Table 33) are considered then potentially the dispersion effect can be anything from 12.7 to 6.6% with an average of recapture indicating an estimate of a 75:25 split between dispersion and deposition. Table 34 outlines the tree recapture across the farm treebelts using the MODASS-OF model, and % recapture is compared with high resolution measurements the treebelt at Poultry 3. In general young, short treebelts with lower tree heights and associated LAIs produce the lowest recapture with Poultry 4 showing a negligible effect. The Poultry 4 treebelt is only 5 years old and had the lowest LAI and tree heights. However, the mature woodland at Dairy 2 with much higher LAI and tree height gave much larger % recapture – albeit LAI and tree height were estimated values as they were not measured in the field. Comparing the model run at Poultry 3 with the high resolution measurements of CO_2 and CH_4 (used a tracer gases to NH_3) gave a fair correlation with the ranges of the measurements. Further analysis would be required to determine the different capture % for CO_2 and CH_4.

Table 34: Percentage canopy recapture of NH_3 by the treebelts across 5 farms using the model MODDAS-OF. A comparison of the model with two high resolution measurements methods is shown at Poultry 3 farm

	% recapture by treebelt					
Recapture calculation method	**Poultry 1**	**Poultry 2**	**Poultry 3**	**Poultry 4**	**Dairy 1**	**Dairy 2**
MODDAS-OPenFoam*	1.0 (roof fans) 1.6 (side ventilated)	1.3	1.7	0.1	4.2	80.6
High resolution measurement CO_2 tracer			6.6			
High resolution measurement CH_4 tracer			0.3			

** Uncertainty of this model is currently ±60%*

Comparisons of tree growth and nutrient uptake by tree species (3.3.1) provides a potentially useful guide to the selection of suitable tree species for future tree planting around livestock buildings. Poplar, Elm, Ash, Birch and Willow grew significantly higher compared to other tree species, while Poplar, Willow, Oak, Ash, Alder, Birch and Elm canopy nitrogen uptake was higher – ranging betwee 20-50 kg N/ha compare to other species where nitrogen uptake was <20 kg N/ha. Whether these speices are better at capturing NH_3 through certain leaf morphologies or are better at assimilating N is uncertain due to other factors like soil type and different ages of treebelts at the farms.

Both the recapture and the reduction in concentrations should be considered as separate outcomes of using trees to reduce impacts of ammonia emissions from agriculture, but in addition the impact of N deposition and the pathways of the N through the ecosystem, soil and hydrological systems should not be forgotten and the long term aim should be to not emit where possible.

The high resolution approach with the CO_2 tracer has significant potential to be used with meteorology to understand in detail the sources on farming landscapes and integrate carbon and nitrogen footprints. Further work to make this type of approach cost effective for farm consultants and the UK Agencies would mean that a systematic approach to quantitative evidence of N emission and reductions can be undertaken. The mix of high resolution measurement in targeted sites and low resolution (passive/ecosystem) approaches should be developed to offer options for evidence gathering. Note that a short term experiment has high risks (COVID, Avian flu) so planning for medium to long term investment in evidence would likely allow more statistical confidence and more useful information to be gathered. It is noted that although it is not a low cost exercise to gather information, the value of the information is very high.

Using high resolution meteorology and accurate measurements (ALPHA and AiRRmonia) to test measurement innovations (e.g. DPAS) should be encouraged in the UK as samplers and sensors are developed to address this urgent environmental problem by UK and international industries and innovators. The intensive experiment, though too short in duration to collect emission factor information (a full poultry shed cycle or full year would be better), showed the capability of looking at carbon and nitrogen footprints, and illustrated the metrological challenge for which agricultural NH_3 and GHG measurements pose. For the state of the art, an eddy covariance approach with a 10 m tower could be used for analysing the footprint of a farm which would be the state of the art. Moreover, protocols for high resolution NH_3 measurements are under development between Environment Agency and UKCEH, and in the next 5 years operational protocols for accurate long term monitoring at both ambient and near source monitoring should become available.

Further benefits that the project has produced include measurement validation of modelled (SCAIL) NH_3 (and vice-versa), which are particularly important for concentrations, and where local landscape emissions are complex. The measurement datasets also provide for validation of future models. Additionally it is recommended that these 5 sites should be revisited in 5 years' time following further growth of the treebelts and development of the farms' C and N emission budgets to begin to build a long term evidence base.

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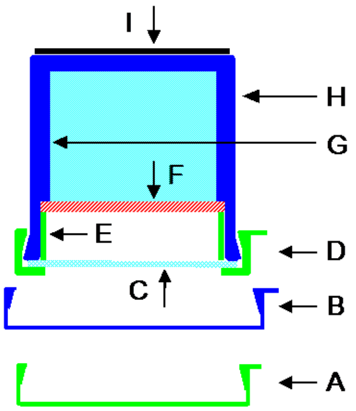
6 Appendices

6.1 NH_3 monitoring method: ALPHA® samplers

Atmospheric NH_3 concentrations were monitored using the UKCEH ALPHA® (**A**dapted **L**ow-cost **P**assive **H**igh **A**bsorption) samplers, shown in Figure 56 (Tang et al., 2001). Triplicate samplers were used to allow an assessment of measurement precision, as part of the quality management process.



A Replacement solid cap
B Top protective cap
C 5 µm PTFE membrane (27 mm diameter)
D Cap with hole for membrane
E Support ring (6 mm height)
F Filter paper
G Internal ridge to support filter paper
H Extended body for ease of handling
I Velcro for attachment to holder

Figure 56. Outline diagram of a single ALPHA sampler.

Preparation of samplers

ALPHA® samplers are prepared in accordance with standard UKCEH protocols (Tang et al. 2019), using filter circles impregnated with 6 mg of citric acid. Replicate samplers (three) are prepared for each monitoring site and placed inside a sealed container, together with replacement solid caps that are used to replace the membrane + membrane caps at the end of sampling.

Exposure of samplers

ALPHA® samplers are attached by the use of Velcro to an aerodynamically shaped support (upturned plant saucer) on a post at about 1.5 m height above ground or vegetation. The sampling height of 1.5 m above ground is standard, providing a representative NH_3 concentration in the atmosphere. Plastic bird spikes (FlockOff) are mounted on the top of the support to deter birds from perching. Replicate samples are used at each site in order to provide an estimate of measurement precision for the air concentration of NH_3 and for QAQC purposes.

Monitoring was on a 2-weekly frequency from August 2020, using continuous time-integrated sampling over each period. In practice, some periods were shorter or longer to 2-weeks, depending on availability of personnel to change samples, weather conditions and site access. The ammonia samplers were prepared and analysed at the UKCEH Edinburgh chemistry laboratory, following standard protocols developed by UKCEH (Tang et al., 2003) and implemented in the UK National Ammonia Monitoring Network (Tang et al., 2018).

ALPHA monitoring sites were set up by an experienced member of staff from UKCEH. After the initial set up, sites were visited by a local site operator that is trained to carry out the required changeover of samples. A recording card was used by the site operator to record dates and times of the samples changes at each site, together with relevant local information (e.g. agricultural activities taking place in the vicinity e.g. muck spreading, during the month or at the time of visit).

Chemical analysis

Exposed samples are stored in a cold room at 4 °C until analysis. Acid impregnated filter circles from the exposed ALPHA® samplers are extracted into deionised water and analysed for ammonium on the SEAL AA3 rapid segmented Continuous Flow Colorimetry system (https://www.seal-analytical.com/) at the UKCEH Laboratory. Ammonia in solution reacts with salicylate and hypochlorite in a buffered alkaline solution in the presence of sodium nitroprusside (pH 12.8 - 13) to form the salicylic acid analog of indophenol blue. The blue-green color produced is measured at 660 nm.

6.1.1 Calculation of air concentrations

The amount of ammonia collected (Q) on an ALPHA® sampler due to air sampling is given by:

$$Q = (c_e - c_b) * v \qquad (1)$$

Where c_e is the liquid concentration of san exposed sampler, c_b is the liquid concentration of a blank sampler and v is the liquid volume of the extraction solution.

The air concentrations (χ_a) of ammonia is then determined as:

$$\chi_a = Q/V \qquad (2)$$

Where V is the effective volume of air sampled (V, m^3), which may be found by:

$$V = DAt/L \qquad (3)$$

Where D is the diffusion coefficient of NH_3 in air, A is the cross sectional area, t is sampling duration and L is the diffusion path length.

6.1.2 QAQC and calibration

The accuracy of the SEAL system for analysis of ammonium in aqueous solution is assured by participation in the WMO-GAW laboratory proficiency testing schemes and by the use of certified reference standards. Replicate (three) ALPHA® samplers are also used for each measurement and should, when performing well, agree to within 15 % (% Coefficient of Variation, % CV). Large discrepancies are most likely due to contamination of samples, or other factors that affect the performance of the samplers. The average reproducibility of replicate samples in the field were generally better than 10 % (CV) and the detection limit (3 σ of blanks) was 0.03 $\mu g\ m^3$ for a monthly exposure period.

A calibrated ammonia uptake rate for the ALPHA® measurements, derived from the parallel measurements between the ALPHA® samplers and a reference active denuder sampling method (DELTA®) (Sutton et al., 2001, Tang et al., 2018, Martins et al., 2018) is applied to the measurement data. Field calibration of the samplers against the active reference method (DELTA®) provides a calibrated ammonia sampling uptake rate for the ALPHA® measurements each year that is applied to the measurement data.

6.2 ALPHA® NH_3 data

[P1 = sampling period 1, the following number is the location of the sampling point]

6.2.1 Poultry 1

Poultry 1		**DATE_OUT**	**DATE_IN**	**(1) ppm NH_4^+**	**(2) ppm NH_4^+**	**(3) ppm NH_4^+**	**Mean ppm NH_4^+**	**% CV**	**Blank ppm NH_4^+**	**NH_3 (µg m^{-3})**	**Comment**
P 1	1	2020/08/06 11:17:00	2020/08/19 11:30:00	-	183.43	193.80	188.61	3.9%	0.064	**528**	
P 1	2	2020/08/06 11:12:00	2020/08/19 11:33:00	8.61	8.68	8.73	8.67	0.7%	0.064	**24.1**	
P 1	3	2020/08/06 11:01:00	2020/08/19 11:36:00	3.88	3.59	3.84	3.77	4.1%	0.064	**10.4**	
P 1	4	2020/08/06 10:17:00	2020/08/19 11:13:00	52.02	52.01	52.04	52.02	0.0%	0.064	***(145)**	Rejected – outside calibration range
P 1	5	2020/08/06 10:30:00	2020/08/19 11:19:00	7.73	7.23	6.85	7.27	6.0%	0.064	**20.1**	
P 1	6	2020/08/06 10:40:00	2020/08/19 11:22:00	3.73	3.99	3.81	3.84	3.5%	0.064	**10.6**	
P 1	7	2020/08/06 11:40:00	2020/08/19 11:45:00	50.33	50.18	50.25	50.26	0.1%	0.064	**141**	
P 1	8	2020/08/06 15:15:00	2020/08/19 11:30:00	5.92	6.19	5.90	6.00	2.7%	0.064	**16.8**	
P 1	9	2020/08/06 11:05:00	2020/08/19 11:39:00	2.94	2.81	2.97	2.91	3.0%	0.064	**7.95**	
P 1	10	2020/08/06 12:07:00	2020/08/19 11:55:00	2.99	3.27	3.21	3.16	4.6%	0.064	**8.67**	
P 2	1	2020/08/19 11:30:00	2020/09/03 09:55:00	166.03	156.18	166.35	162.85	3.5%	0.073	**397**	
P 2	2	2020/08/19 11:33:00	2020/09/03 10:05:00	23.00	20.55	16.55	20.03	16.3%	0.073	**48.7**	
P 2	3	2020/08/19 11:36:00	2020/09/03 10:12:00	3.72	3.46	3.63	3.60	3.8%	0.073	**8.61**	
P 2	4	2020/08/19 11:13:00	2020/09/03 10:56:00	172.55	176.08	186.40	178.34	4.0%	0.073	**433**	
P 2	5	2020/08/19 11:19:00	2020/09/03 10:41:00	11.17	10.77	10.84	10.93	1.9%	0.073	**26.4**	
P 2	6	2020/08/19 11:22:00	2020/09/03 10:50:00	3.51	3.51	3.44	3.49	1.1%	0.073	**8.31**	
P 2	7	2020/08/19 11:45:00	2020/09/03 10:32:00	70.13	68.57	74.91	71.20	4.6%	0.073	**173**	
P 2	8	2020/08/19 11:42:00	2020/09/03 10:25:00	6.12	5.57	5.15	5.61	8.6%	0.073	**13.5**	
P 2	9	2020/08/19 11:39:00	2020/09/03 10:18:00	2.70	2.59	2.79	2.69	3.8%	0.073	**6.39**	
P 2	10	2020/08/19 11:55:00	2020/09/03 11:12:00	1.09	1.03	1.05	1.06	2.8%	0.073	**2.39**	
P 3	1	2020/09/03 09:55:00	2020/09/25 12:05:00	410.72	364.54	358.32	377.86	7.6%	0.089	**623**	
P 3	2	2020/09/03 10:05:00	2020/09/25 12:03:00	41.20	41.50	44.43	42.37	4.2%	0.089	**69.7**	
P 3	3	2020/09/03 10:12:00	2020/09/25 12:00:00	7.52	7.50	7.48	7.50	0.3%	0.089	**12.2**	
P 3	4	2020/09/03 10:56:00	2020/09/25 12:16:00	296.14	302.81	331.67	310.21	6.1%	0.089	**512**	
P 3	5	2020/09/03 10:41:00	2020/09/25 12:08:00	15.97	15.68	17.26	16.30	5.1%	0.089	**26.8**	
P 3	6	2020/09/03 10:50:00	2020/09/25 12:20:00	5.49	6.02	5.67	5.72	4.7%	0.089	**9.30**	
P 3	7	2020/09/03 10:32:00	2020/09/25 11:51:00	45.26	56.93	62.30	54.83	15.9%	0.089	**90.4**	%CV > 15%
P 3	8	2020/09/03 10:25:00	2020/09/25 11:54:00	12.13	12.61	13.33	12.69	4.7%	0.089	**20.8**	
P 3	9	2020/09/03 11:18:00	2020/09/25 11:57:00	6.29	7.02	6.92	6.74	5.9%	0.089	**11.0**	
P 3	10	2020/09/03 11:12:00	2020/09/25 12:25:00	4.01	3.65	3.83	3.83	4.7%	0.089	**6.18**	

P 4	1	2020/09/25 12:06:00	2020/09/30 13:55:00	29.30	25.21	26.27	26.93	7.9%	0.092	**193**	
P 4	2	2020/09/25 12:03:00	2020/09/30 13:52:00	1.75	2.29	1.90	1.98	14.1%	0.092	**13.5**	
P 4	3	2020/09/25 12:00:00	2020/09/30 13:50:00	0.71	0.63	0.71	0.68	6.2%	0.092	**4.24**	
P 4	4	2020/09/25 12:17:00	2020/09/30 14:08:00	8.06	7.37	7.75	7.72	4.4%	0.092	**54.8**	
P 4	5	2020/09/25 12:09:00	2020/09/30 14:00:00	1.24	1.52	1.32	1.36	10.6%	0.092	**9.10**	
P 4	6	2020/09/25 12:23:00	2020/09/30 14:03:00	0.67	0.60	0.66	0.65	5.9%	0.092	**3.98**	
P 4	7	2020/09/25 11:52:00	2020/09/30 13:41:00	16.54	15.67	16.22	16.14	2.7%	0.092	**115**	
P 4	8	2020/09/25 11:55:00	2020/09/30 13:44:00	1.90	1.69	1.72	1.77	6.5%	0.092	**12.1**	
P 4	9	2020/09/25 11:57:00	2020/09/30 13:47:00	0.83	0.65	0.71	0.73	12.6%	0.092	**4.57**	
P 4	10	2020/09/25 12:26:00	2020/09/30 14:19:00	0.87	0.88	0.87	0.88	0.6%	0.092	**5.62**	
P 5	1	2020/09/30 13:55:00	2020/10/19 13:33:00	177.92	173.11	168.10	173.04	2.8%	0.089	**332**	
P 5	2	2020/09/30 13:52:00	2020/10/19 13:31:00	14.86	14.65	15.29	14.93	2.2%	0.089	**28.5**	
P 5	3	2020/09/30 13:50:00	2020/10/19 13:30:00	2.96	3.14	3.20	3.10	4.1%	0.089	**5.77**	
P 5	4	2020/09/30 14:08:00	2020/10/19 13:41:00	129.21	132.34	137.15	132.90	3.0%	0.089	**255**	
P 5	5	2020/09/30 14:00:00	2020/10/19 13:35:00	7.66	7.23	7.92	7.60	4.6%	0.089	**14.4**	
P 5	6	2020/09/30 14:03:00	2020/10/19 13:43:00	3.32	3.55	3.40	3.42	3.3%	0.089	**6.40**	
P 5	7	2020/09/30 13:41:00	2020/10/19 13:19:00	68.41	70.07	63.54	67.34	5.0%	0.089	**129**	
P 5	8	2020/09/30 13:44:00	2020/10/19 13:22:00	12.74	12.40	12.72	12.62	1.5%	0.089	**24.0**	
P 5	9	2020/09/30 13:47:00	2020/10/19 12:25:00	2.57	2.78	2.46	2.60	6.2%	0.089	**4.83**	
P 5	10	2020/09/30 14:19:00	-	-	-	-	-	-	0.089	**-**	Not set out

6.2.2 Dairy 1

Dairy 1		DATE_OUT	DATE_IN	(1) ppm NH_4^+	(2) ppm NH_4^+	(3) ppm NH_4^+	Mean ppm NH_4^+	% CV	Blank ppm NH_4^+	NH_3 (µg m^{-3})	Comment
P 1	1	2020/08/05 16:36:00	2020/08/19 09:20:00	11.20	11.41	11.94	11.52	3.3%	0.064	**30.5**	
P 1	2	2020/08/05 16:15:00	2020/08/19 09:24:00	4.75	4.68	4.43	4.62	3.7%	0.064	**12.1**	
P 1	3	2020/08/05 17:58:00	2020/08/19 09:13:00	0.71	0.70	-	0.70	1.5%	0.064	**1.71**	
P 1	4	2020/08/05 17:35:00	2020/08/19 09:27:00	3.99	3.87	3.91	3.92	1.5%	0.064	**10.3**	
P 1	5	2020/08/05 17:20:00	2020/08/19 09:40:00	1.44	1.52	1.47	1.48	2.9%	0.064	**3.76**	
P 1	6	2020/08/05 17:07:00	2020/08/19 09:48:00	1.52	1.40	1.34	1.42	6.5%	0.064	**3.61**	
P 1	7	2020/08/05 18:11:00	2020/08/19 10:04:00	11.29	12.24	11.29	11.60	4.7%	0.064	**30.8**	
P 1	8	2020/08/05 18:27:00	2020/08/19 10:13:00	3.76	4.14	3.92	3.94	4.8%	0.064	**10.3**	
P 1	9	2020/08/05 18:20:00	2020/08/19 10:10:00	4.07	3.99	4.12	4.06	1.6%	0.064	**10.7**	
P 1	10	2020/08/05 18:45:00	2020/08/19 10:24:00	5.29	5.09	5.31	5.23	2.3%	0.064	**13.8**	
P 2	1	2020/08/19 09:20:00	2020/09/03 13:54:00	10.52	11.21	10.71	10.81	3.3%	0.073	**25.8**	
P 2	2	2020/08/19 09:24:00	2020/09/03 13:57:00	6.98	6.35	6.63	6.65	4.7%	0.073	**15.8**	
P 2	3	2020/08/19 09:13:00	2020/09/03 13:28:00	74.99	74.57	63.45	71.00	9.2%	0.073	**170**	
P 2	4	2020/08/19 09:27:00	2020/09/03 13:59:00	5.99	5.64	5.67	5.77	3.4%	0.073	**13.7**	
P 2	5	2020/08/19 09:40:00	2020/09/03 14:16:00	2.79	2.67	2.49	2.65	5.7%	0.073	**6.17**	
P 2	6	2020/08/19 09:48:00	2020/09/03 14:20:00	1.93	1.88	1.82	1.88	3.0%	0.073	**4.32**	
P 2	7	2020/08/19 10:04:00	2020/09/03 13:47:00	16.48	16.98	17.16	16.87	2.1%	0.073	**40.4**	
P 2	8	2020/08/19 10:13:00	2020/09/03 13:38:00	9.48	9.49	9.57	9.52	0.5%	0.073	**22.7**	
P 2	9	2020/08/19 10:10:00	2020/09/03 13:41:00	11.78	10.77	10.79	11.11	5.2%	0.073	**26.6**	
P 2	10	2020/08/19 10:24:00	2020/09/03 13:57:00	2.11	2.00	2.17	2.09	4.2%	0.073	**4.86**	
P 3	1	2020/09/03 13:54:00	2020/09/24 10:11:00	13.04	12.55	12.08	12.55	3.8%	0.089	**21.8**	
P 3	2	2020/09/03 13:57:00	2020/09/24 10:44:00	7.79	7.42	7.46	7.56	2.7%	0.089	**13.0**	
P 3	3	2020/09/03 13:30:00	2020/09/24 10:30:00	87.58	88.73	90.87	89.06	1.9%	0.089	**155**	
P 3	4	2020/09/03 14:10:00	2020/09/24 10:53:00	8.42	8.85	8.48	8.58	2.7%	0.089	**14.8**	
P 3	5	2020/09/03 14:16:00	2020/09/24 10:08:00	3.42	4.26	3.43	3.70	13.0%	0.089	**6.32**	
P 3	6	2020/09/03 14:20:00	2020/09/24 10:18:00	4.93	5.34	5.02	5.09	4.2%	0.089	**8.75**	
P 3	7	2020/09/03 13:48:00	2020/09/24 10:22:00	43.74	44.48	40.44	42.88	5.0%	0.089	**74.7**	
P 3	8	2020/09/03 13:38:00	2020/09/24 10:36:00	5.21	5.24	4.96	5.14	2.9%	0.089	**8.81**	
P 3	9	2020/09/03 13:41:00	2020/09/24 10:56:00	7.10	7.32	6.77	7.06	4.0%	0.089	**12.2**	
P 3	10	2020/09/03 14:09:00	2020/09/24 11:13:00	4.47	4.33	4.30	4.37	2.0%	0.089	**7.46**	
P 4	1	2020/09/24 10:15:00	2020/09/30 12:14:00	2.52	2.65	2.73	2.63	4.1%	0.092	**15.2**	
P 4	2	2020/09/24 10:44:00	2020/09/30 12:17:00	1.83	1.68	1.72	1.74	4.6%	0.092	**9.91**	
P 4	3	2020/09/24 10:31:00	2020/09/30 12:09:00	-	21.15	20.24	20.70	3.1%	0.092	**124**	
P 4	4	2020/09/24 10:54:00	2020/09/30 12:19:00	1.48	1.49	1.56	1.51	2.9%	0.092	**8.51**	

P 4	5	2020/09/24 10:09:00	2020/09/30 12:33:00	0.63	0.64	0.64	0.64	1.1%	0.092	**3.27**	
P 4	6	2020/09/24 10:20:00	2020/09/30 12:36:00	0.43	0.41	0.49	0.44	8.9%	0.092	**2.09**	
P 4	7	2020/09/24 10:23:00	2020/09/30 11:57:00	6.32	6.00	6.12	6.14	2.6%	0.092	**36.3**	
P 4	8	2020/09/24 10:37:00	2020/09/30 12:04:00	5.72	5.00	5.13	5.28	7.3%	0.092	**31.2**	
P 4	9	2020/09/24 10:57:00	2020/09/30 12:02:00	6.16	5.92	6.04	6.04	2.0%	0.092	**35.8**	
P 4	10	2020/09/24 11:14:00	2020/09/30 12:47:00	1.31	1.21	1.31	1.27	4.4%	0.092	**7.10**	
P 5	1	2020/09/30 12:14:00	2020/10/19 11:28:00	10.84	9.44	10.23	10.17	6.9%	0.089	**19.4**	
P 5	2	2020/09/30 12:17:00	2020/10/19 11:34:00	5.68	5.61	5.44	5.58	2.2%	0.089	**10.5**	
P 5	3	2020/09/30 12:09:00	2020/10/19 11:25:00	63.29	65.06	62.09	63.48	2.4%	0.089	**122**	
P 5	4	2020/09/30 12:19:00	2020/10/19 11:31:00	5.55	5.39	5.24	5.39	2.9%	0.089	**10.2**	
P 5	5	2020/09/30 12:33:00	2020/10/19 11:46:00	1.35	1.26	1.39	1.33	4.9%	0.089	**2.39**	
P 5	6	2020/09/30 12:36:00	2020/10/19 11:50:00	1.16	1.11	1.12	1.13	2.6%	0.089	**2.00**	
P 5	7	2020/09/30 11:57:00	2020/10/19 11:19:00	20.88	22.26	18.85	20.66	8.3%	0.089	**39.5**	
P 5	8	2020/09/30 12:04:00	2020/10/19 11:10:00	9.41	8.51	8.28	8.73	6.8%	0.089	**16.6**	
P 5	9	2020/09/30 12:02:00	2020/10/19 11:14:00	11.71	11.42	12.01	11.71	2.5%	0.089	**22.3**	
P 5	10	2020/09/30 12:47:00	2020/10/19 12:05:00	1.88	1.84	1.80	1.84	2.1%	0.089	**3.36**	
P 6	1	2020/10/19 11:28:00	2020/10/30 12:18:00	9.62	10.88	11.15	10.55	7.8%	0.068	**34.5**	
P 6	2	2020/10/19 11:34:00	2020/10/30 12:21:00	5.69	5.73	5.42	5.61	3.1%	0.068	**18.2**	
P 6	3	2020/10/19 11:25:00	2020/10/30 12:29:00	42.53	-	42.55	42.54	0.0%	0.068	**140**	
P 6	4	2020/10/19 11:31:00	2020/10/30 12:23:00	5.54	5.53	5.81	5.63	2.8%	0.068	**18.3**	
P 6	5	2020/10/19 11:46:00	2020/10/30 11:54:00	2.17	2.09	2.16	2.14	2.1%	0.068	**6.82**	
P 6	6	2020/10/19 11:50:00	2020/10/30 11:59:00	1.65	1.50	1.44	1.53	7.2%	0.068	**4.81**	
P 6	7	2020/10/19 11:19:00	2020/10/30 12:43:00	17.27	18.23	19.28	18.26	5.5%	0.068	**59.7**	
P 6	8	2020/10/19 11:10:00	2020/10/30 12:36:00	0.63	0.65	0.60	0.63	3.4%	0.068	**1.83**	
P 6	9	2020/10/19 11:14:00	2020/10/30 12:39:00	0.76	0.86	0.87	0.83	6.7%	0.068	**2.49**	
P 6	10	2020/10/19 12:05:00	2020/10/30 12:58:00	0.40	0.43	0.39	0.41	5.3%	0.068	**1.12**	
P 7	1	2020/10/30 12:18:00	2020/11/11 10:48:00	8.45	8.27	8.25	8.32	1.3%	0.061	**25.2**	
P 7	2	2020/10/30 12:21:00	2020/11/11 10:51:00	3.65	3.49	3.60	3.58	2.3%	0.061	**10.7**	
P 7	3	2020/10/30 12:29:00	2020/11/11 10:41:00	64.28	100.37	54.68	73.11	33.0%	0.061	**223**	%CV > 15%
P 7	4	2020/10/30 12:23:00	2020/11/11 10:53:00	3.98	4.12	3.98	4.03	2.1%	0.061	**12.1**	
P 7	5	2020/10/30 12:43:00	2020/11/11 11:10:00	1.36	1.35	1.50	1.40	5.7%	0.061	**4.09**	
P 7	6	2020/10/30 11:59:00	2020/11/11 11:13:00	1.05	1.11	1.01	1.05	4.9%	0.061	**3.02**	
P 7	7	2020/10/30 12:43:00	2020/11/11 10:28:00	15.75	15.68	16.52	15.98	2.9%	0.061	**48.7**	
P 7	8	2020/10/30 12:36:00	2020/11/11 10:20:00	3.08	2.76	2.55	2.80	9.6%	0.061	**8.37**	
P 7	9	2020/10/30 12:39:00	2020/11/11 10:23:00	3.10	3.47	3.00	3.19	7.7%	0.061	**9.57**	
P 7	10	2020/10/30 12:58:00	2020/11/11 11:20:00	-	-	-	-	-	0.061	**-**	

6.2.3 Poultry 2

Poultry 2		**DATE_OUT**	**DATE_IN**	**(1) ppm NH_4^+**	**(2) ppm NH_4^+**	**(3) ppm NH_4^+**	**Mean ppm NH_4^+**	**% CV**	**Blank ppm NH_4^+**	**NH_3 (µg m^{-3})**	**Comment**
P 1	1	2020/08/04 14:31:00	2020/08/18 10:39:00	1.86	2.01	1.77	1.88	6.4%	0.064	**4.78**	
P 1	2	2020/08/04 14:31:00	2020/08/18 10:35:00	1.41	1.80	-	1.61	16.9%	0.064	**4.06**	%CV > 15%
P 1	3	2020/08/04 13:35:00	2020/08/18 10:32:00	0.89	0.87	0.88	0.88	1.0%	0.064	**2.14**	
P 1	4	2020/08/04 13:14:00	2020/08/18 10:25:00	0.89	0.84	0.93	0.89	4.9%	0.064	**2.16**	
P 1	5	2020/08/04 13:25:00	2020/08/18 10:28:00	0.97	0.98	1.00	0.98	2.0%	0.064	**2.41**	
P 1	6	2020/08/04 13:54:00	2020/08/18 10:15:00	1.03	1.03	0.90	0.99	7.6%	0.064	**2.43**	
P 1	7	2020/08/04 14:02:00	2020/08/18 10:20:00	0.99	0.99	0.98	0.99	0.8%	0.064	**2.43**	
P 1	8	2020/08/04 14:11:00	2020/08/18 10:07:00	1.08	1.08	1.12	1.09	2.1%	0.064	**2.70**	
P 1	9	2020/08/04 14:21:00	2020/08/18 10:10:00	1.05	1.02	1.02	1.03	1.8%	0.064	**2.55**	
P 1	10	2020/08/04 14:45:00	2020/08/18 09:55:00	0.98	1.11	0.99	1.03	7.2%	0.064	**2.54**	
P 2	1	2020/08/18 10:39:00	2020/09/03 10:44:00	10.73	9.57	9.66	9.98	6.5%	0.073	**22.6**	
P 2	2	2020/08/18 10:35:00	2020/09/03 10:37:00	3.58	3.59	3.12	3.43	7.8%	0.073	**7.64**	
P 2	3	2020/08/18 10:32:00	2020/09/03 10:30:00	1.79	1.51	1.48	1.59	10.8%	0.073	**3.46**	
P 2	4	2020/08/18 10:25:00	2020/09/03 10:24:00	5.03	4.75	5.13	4.97	4.0%	0.073	**11.1**	
P 2	5	2020/08/18 10:28:00	2020/09/03 10:27:00	2.59	2.62	2.81	2.67	4.6%	0.073	**5.92**	
P 2	6	2020/08/18 10:15:00	2020/09/03 10:18:00	4.27	4.42	4.32	4.34	1.8%	0.073	**9.71**	
P 2	7	2020/08/18 10:20:00	2020/09/03 10:21:00	2.04	1.94	1.94	1.97	2.9%	0.073	**4.32**	
P 2	8	2020/08/18 10:07:00	2020/09/03 10:09:00	4.89	4.59	4.35	4.61	5.8%	0.073	**10.3**	
P 2	9	2020/08/18 10:10:00	2020/09/03 10:13:00	1.53	1.61	1.65	1.60	3.7%	0.073	**3.47**	
P 2	10	2020/08/18 09:55:00	2020/09/03 10:54:00	2.58	2.51	2.49	2.53	1.9%	0.073	**5.57**	
P 3	1	2020/09/03 10:44:00	2020/09/25 10:48:00	33.17	29.79	34.43	32.46	7.4%	0.089	**53.6**	
P 3	2	2020/09/03 10:37:00	2020/09/25 10:31:00	8.32	8.25	8.82	8.46	3.7%	0.089	**13.9**	
P 3	3	2020/09/03 10:30:00	2020/09/25 10:34:00	5.40	4.88	5.12	5.13	5.1%	0.089	**8.35**	
P 3	4	2020/09/03 10:24:00	2020/09/25 10:38:00	31.86	30.75	32.70	31.77	3.1%	0.089	**52.4**	
P 3	5	2020/09/03 10:27:00	2020/09/25 10:36:00	18.92	18.92	18.89	18.91	0.1%	0.089	**31.1**	
P 3	6	2020/09/03 10:18:00	2020/09/25 10:43:00	31.12	29.99	33.63	31.58	5.9%	0.089	**52.1**	
P 3	7	2020/09/03 10:21:00	2020/09/25 10:41:00	12.59	12.49	12.89	12.66	1.7%	0.089	**20.8**	
P 3	8	2020/09/03 10:09:00	2020/09/25 10:22:00	12.26	12.37	11.34	11.99	4.7%	0.089	**19.7**	
P 3	9	2020/09/03 10:13:00	2020/09/25 10:24:00	3.07	3.30	3.05	3.14	4.5%	0.089	**5.05**	
P 3	10	2020/09/03 10:54:00	2020/09/25 10:56:00	2.30	2.53	2.27	2.37	5.9%	0.089	**3.77**	
P 4	1	2020/09/25 10:50:00	2020/09/30 09:33:00	8.23	7.74	7.72	7.90	3.6%	0.092	**57.5**	
P 4	2	2020/09/25 10:32:00	2020/09/30 09:17:00	1.01	1.08	1.06	1.05	3.2%	0.092	**7.06**	
P 4	3	2020/09/25 10:35:00	2020/09/30 09:20:00	0.67	0.70	0.70	0.69	2.3%	0.092	**4.40**	
P 4	4	2020/09/25 10:39:00	2020/09/30 09:30:00	1.04	0.96	0.91	0.97	7.0%	0.092	**6.45**	

P 4	5	2020/09/25 10:37:00	2020/09/30 09:22:00	0.74	0.70	0.72	0.72	2.7%	0.092	**4.60**	
P 4	6	2020/09/25 10:44:00	2020/09/30 09:27:00	1.56	1.62	1.75	1.64	5.7%	0.092	**11.4**	
P 4	7	2020/09/25 10:41:00	2020/09/30 09:25:00	0.71	0.64	0.69	0.68	5.0%	0.092	**4.34**	
P 4	8	2020/09/25 10:22:00	2020/09/30 09:37:00	7.98	7.27	7.85	7.70	4.9%	0.092	**55.8**	
P 4	9	2020/09/25 10:25:00	2020/09/30 09:39:00	2.20	2.17	2.33	2.23	4.0%	0.092	**15.7**	
P 4	10	2020/09/25 10:57:00	2020/09/30 09:48:00	0.64	0.67	0.62	0.64	4.3%	0.092	**4.05**	
P 5	1	2020/09/30 09:33:00	2020/10/15 09:06:00	19.00	20.91	25.37	21.76	15.0%	0.089	**52.7**	
P 5	2	2020/09/30 09:17:00	2020/10/15 09:09:00	4.56	4.51	4.92	4.66	4.7%	0.089	**11.1**	
P 5	3	2020/09/30 09:20:00	2020/10/15 09:14:00	1.90	1.86	1.82	1.86	2.3%	0.089	**4.31**	
P 5	4	2020/09/30 09:30:00	2020/10/15 09:18:00	10.18	10.52	8.68	9.79	10.0%	0.089	**23.6**	
P 5	5	2020/09/30 09:22:00	2020/10/15 09:15:00	5.61	5.41	5.22	5.41	3.7%	0.089	**12.9**	
P 5	6	2020/09/30 09:27:00	2020/10/15 09:22:00	19.22	19.36	19.57	19.38	0.9%	0.089	**46.8**	
P 5	7	2020/09/30 09:25:00	2020/10/15 09:20:00	8.35	8.05	8.82	8.40	4.6%	0.089	**20.2**	
P 5	8	2020/09/30 09:37:00	2020/10/15 09:25:00	20.81	21.40	21.02	21.08	1.4%	0.089	**51/0**	
P 5	9	2020/09/30 09:39:00	2020/10/15 09:28:00	3.90	3.79	4.10	3.93	4.0%	0.089	**9.33**	
P 5	10	2020/09/30 09:48:00	2020/10/15 09:45:00	1.28	1.24	1.30	1.27	2.2%	0.089	**2.87**	

6.2.4 Dairy 2

Dairy 2		DATE_OUT	DATE_IN	(1) ppm NH_4^+	(2) ppm NH_4^+	(3) ppm NH_4^+	Mean ppm NH_4^+	% CV	Blank ppm NH_4^+	NH_3 (µg m^{-3})	Comment
P 1	1	2020/08/05 10:38:00	2020/08/18 11:57:00	3.94	3.98	3.89	3.94	1.2%	0.064	**10.8**	
P 1	2	2020/08/05 10:52:00	2020/08/18 12:39:00	3.45	2.41	2.74	2.86	18.6%	0.064	**7.80**	%CV > 15%
P 1	3	2020/08/05 12:55:00	2020/08/18 12:10:00	1.08	1.08	1.14	1.10	3.1%	0.064	**2.90**	
P 1	4	2020/08/13 15:00:00	2020/08/18 12:49:00	0.57	0.53	0.57	0.56	4.0%	0.064	**3.65**	Damaged by cows Replaced on 13/08
P 1	5	2020/08/05 11:45:00	2020/08/18 11:52:00	6.69	5.79	6.02	6.17	7.6%	0.064	**17.1**	
P 1	6	2020/08/05 11:57:00	2020/08/18 12:01:00	3.78	3.91	3.88	3.86	1.7%	0.064	**10.6**	
P 1	7	2020/08/05 12:15:00	2020/08/18 12:32:00	2.43	2.39	2.54	2.45	3.1%	0.064	**6.68**	
P 1	8	2020/08/05 12:35:00	2020/08/18 12:20:00	1.04	0.96	-	1.00	6.1%	0.064	**2.63**	
P 1	9	2020/08/05 14:06:00	2020/08/18 12:53:00	1.66	1.56	1.60	1.61	3.1%	0.064	**4.34**	
P 1	10	2020/08/05 14:40:00	2020/08/18 13:13:00	3.30	3.16	3.44	3.30	4.3%	0.064	**9.12**	
P 2	1	2020/08/18 11:57:00	2020/09/03 12:54:00	5.46	5.77	5.28	5.50	4.5%	0.073	**12.3**	
P 2	2	2020/08/18 12:39:00	2020/09/03 12:25:00	3.40	4.04	4.08	3.84	9.9%	0.073	**8.58**	
P 2	3	2020/08/18 12:49:00	2020/09/03 12:10:00	0.96	1.09	1.11	1.05	7.7%	0.073	**2.24**	
P 2	4	2020/08/18 12:49:00	2020/09/03 12:10:00	0.96	1.11	1.02	1.03	7.1%	0.073	**2.18**	
P 2	5	2020/08/18 11:52:00	2020/09/03 12:58:00	9.42	10.44	9.52	9.79	5.8%	0.073	**22.1**	
P 2	6	2020/08/18 12:01:00	2020/09/03 12:51:00	5.84	5.60	5.54	5.66	2.8%	0.073	**12.7**	
P 2	7	2020/08/18 12:32:00	2020/09/03 12:48:00	2.73	2.68	2.51	2.64	4.4%	0.073	**5.84**	
P 2	8	2020/08/18 12:20:00	2020/09/03 12:38:00	0.67	0.62	0.65	0.65	3.9%	0.073	**1.31**	
P 2	9	2020/08/18 12:53:00	2020/09/03 12:14:00	1.14	1.21	1.10	1.15	4.7%	0.073	**2.45**	
P 2	10	2020/08/18 13:13:00	2020/09/03 13:09:00	2.66	2.91	2.66	2.75	5.3%	0.073	**6.08**	
P 3	1	2020/09/03 13:54:00	2020/09/24 12:01:00	3.10	-	-	3.10	-	0.089	**5.25**	2 missing
P 3	2	2020/09/03 13:57:00	2020/09/24 12:04:00	5.47	5.17	4.94	5.19	5.1%	0.089	**8.88**	
P 3	3	2020/09/03 13:28:00	2020/09/24 11:56:00	1.81	2.01	2.05	1.96	6.8%	0.089	**3.25**	
P 3	4	2020/09/03 13:59:00	2020/09/24 12:09:00	1.26	1.25	1.32	1.27	3.0%	0.089	**2.06**	
P 3	5	2020/09/03 14:16:00	2020/09/24 12:22:00	16.03	16.37	18.73	17.04	8.6%	0.089	**29.5**	
P 3	6	2020/09/03 14:20:00	2020/09/24 12:28:00	10.62	-	-	10.62	-	0.089	**18.3**	2 missing
P 3	7	2020/09/03 13:47:00	2020/09/24 11:51:00	7.14	6.63	6.58	6.78	4.6%	0.089	**11.7**	
P 3	8	2020/09/03 13:38:00	2020/09/24 11:43:00	1.35	1.45	1.36	1.39	4.1%	0.089	**2.26**	
P 3	9	2020/09/03 13:41:00	2020/09/24 11:47:00	1.46	1.52	1.50	1.49	2.1%	0.089	**2.44**	
P 3	10	2020/09/03 14:40:00	2020/09/24 12:50:00	3.59	3.71	3.66	3.66	1.6%	0.089	**6.21**	
P 4	1	2020/09/24 12:02:00	2020/09/30 10:41:00	4.17	3.88	4.36	4.14	5.8%	0.092	**24.8**	
P 4	2	2020/09/24 12:05:00	2020/09/30 11:03:00	2.69	2.56	3.13	2.79	10.6%	0.092	**16.5**	
P 4	3	2020/09/24 11:56:00	2020/09/30 10:52:00	0.49	0.42	0.44	0.45	8.7%	0.092	**2.18**	

P 4	4	2020/09/24 12:09:00	2020/09/30 11:11:00	0.33	0.36	0.31	0.33	6.4%	0.092	**1.48**	
P 4	5	2020/09/24 12:23:00	2020/09/30 10:38:00	5.65	5.73	5.62	5.67	1.0%	0.092	**34.3**	
P 4	6	2020/09/24 12:29:00	2020/09/30 10:44:00	3.52	3.28	3.27	3.35	4.2%	0.092	**20.0**	
P 4	7	2020/09/24 11:51:00	2020/09/30 10:47:00	1.38	1.42	1.33	1.38	3.1%	0.092	**7.9**	
P 4	8	2020/09/24 11:44:00	2020/09/30 10:57:00	0.28	0.32	-	0.30	8.4%	0.092	**1.28**	
P 4	9	2020/09/24 11:47:00	2020/09/30 11:14:00	0.42	0.58	0.47	0.49	16.1%	0.092	**2.42**	%CV > 15%
P 4	10	2020/09/24 12:51:00	2020/09/30 11:32:00	1.07	1.02	1.01	1.03	2.8%	0.092	**5.77**	
P 5	1	2020/09/30 10:41:00	2020/10/15 11:36:00	8.18	8.62	8.45	8.42	2.6%	0.089	**20.2**	
P 5	2	2020/09/30 11:03:00	2020/10/15 11:10:00	6.23	5.86	-	6.05	4.3%	0.089	**14.5**	
P 5	3	2020/09/30 10:52:00	2020/10/15 11:18:00	1.65	1.90	1.79	1.78	6.9%	0.089	**4.10**	
P 5	4	2020/09/30 11:11:00	2020/10/15 10:55:00	0.96	1.15	0.96	1.02	10.8%	0.089	**2.26**	
P 5	5	2020/09/30 10:38:00	2020/10/15 11:39:00	14.84	15.53	14.49	14.95	3.5%	0.089	**36.0**	
P 5	6	2020/09/30 10:44:00	2020/10/15 11:33:00	10.82	10.36	10.16	10.45	3.2%	0.089	**25.1**	
P 5	7	2020/09/30 10:47:00	2020/10/15 11:30:00	5.77	5.21	4.87	5.28	8.7%	0.089	**12.6**	
P 5	8	2020/09/30 10:57:00	2020/10/15 11:22:00	0.72	0.74	0.77	0.75	3.3%	0.089	**1.60**	
P 5	9	2020/09/30 11:14:00	2020/10/15 11:01:00	1.46	1.47	1.52	1.48	2.2%	0.089	**3.39**	
P 5	10	2020/09/30 11:32:00	2020/10/15 11:17:00	1.31	1.34	1.30	1.32	1.6%	0.089	**2.99**	
P 6	1	2020/10/15 11:36:00	2020/10/29 10:40:00	2.72	2.82	2.58	2.71	4.4%	0.068	**6.87**	
P 6	2	2020/10/15 11:10:00	2020/10/29 11:05:00	2.02	1.77	1.73	1.84	8.5%	0.068	**4.59**	
P 6	3	2020/10/15 11:18:00	2020/10/29 10:50:00	0.78	0.85	0.74	0.79	6.9%	0.068	**1.87**	
P 6	4	2020/10/15 10:55:00	2020/10/29 11:14:00	0.94	0.84	0.98	0.92	7.5%	0.068	**2.21**	
P 6	5	2020/10/15 11:39:00	2020/10/29 10:36:00	5.11	5.15	5.15	5.14	0.5%	0.068	**13.2**	
P 6	6	2020/10/15 11:33:00	2020/10/29 10:43:00	3.40	3.20	3.23	3.28	3.3%	0.068	**8.35**	
P 6	7	2020/10/15 11:30:00	2020/10/29 10:46:00	2.33	2.13	2.17	2.21	4.7%	0.068	**5.57**	
P 6	8	2020/10/15 11:22:00	2020/10/29 10:56:00	0.62	0.57	0.62	0.60	4.7%	0.068	**1.38**	
P 6	9	2020/10/15 11:01:00	2020/10/29 11:18:00	0.94	0.92	0.98	0.94	3.4%	0.068	**2.27**	
P 6	10	2020/10/15 11:17:00	2020/10/29 11:40:00	4.62	4.65	5.15	4.81	6.2%	0.068	**12.3**	
P 7	1	2020/10/29 10:40:00	2020/11/11 12:02:00	3.86	3.96	4.08	3.96	2.8%	0.061	**10.9**	
P 7	2	2020/10/29 11:05:00	2020/11/11 12:27:00	2.38	2.51	2.45	2.44	2.7%	0.061	**6.62**	
P 7	3	2020/10/29 10:50:00	2020/11/11 12:15:00	0.96	1.12	1.09	1.06	8.0%	0.061	**2.76**	
P 7	4	2020/10/29 11:14:00	2020/11/11 12:37:00	0.81	0.73	0.65	0.73	10.8%	0.061	**1.85**	
P 7	5	2020/10/29 10:36:00	2020/11/11 11:59:00	7.89	8.44	8.36	8.23	3.6%	0.061	**22.7**	
P 7	6	2020/10/29 10:43:00	2020/11/11 12:04:00	5.11	4.60	5.10	4.94	6.0%	0.061	**13.6**	
P 7	7	2020/10/29 10:46:00	2020/11/11 12:07:00	2.91	3.18	3.17	3.09	4.9%	0.061	**8.4**	
P 7	8	2020/10/29 10:56:00	2020/11/11 12:21:00	0.76	0.73	0.79	0.76	3.7%	0.061	**1.94**	
P 7	9	2020/10/29 11:18:00	2020/11/11 12:41:00	1.08	0.81	0.76	0.88	19.4%	0.061	**2.29**	%CV > 15%
P 7	10	2020/10/29 11:40:00	2020/11/11 12:53:00	-	-	-	-	-	0.061	**-**	

P 8	1	-	-	5.77	6.56	5.91	6.08	6.9%	0.097	-	No
P 8	2	-	-	4.06	4.10	4.26	4.14	2.6%	0.097	-	Sample
P 8	3	-	-	1.72	1.87	1.71	1.77	4.9%	0.097	-	Info.
P 8	4	-	-	0.83	0.95	0.84	0.88	7.6%	0.097	-	For
P 8	5	-	-	12.82	12.25	12.25	12.44	2.6%	0.097	-	Period 8
P 8	6	-	-	8.22	7.99	8.01	8.08	1.6%	0.097	-	
P 8	7	-	-	4.65	4.33	4.22	4.40	5.1%	0.097	-	
P 8	8	-	-	1.08	1.01	1.10	1.06	4.7%	0.097	-	
P 8	9	-	-	1.16	1.01	1.02	1.07	7.9%	0.097	-	
P 8	10	-	-	-	-	-	-	-	0.097	-	

6.2.5 Poultry 3 - Poultry 4

Period	Poultry 4 Poultry 3	DATE_OUT	DATE_IN	(1) ppm NH_4^+	(2) ppm NH_4^+	(3) ppm NH_4^+	Mean ppm NH_4^+	% CV	Blank ppm NH_4^+	NH_3 (μg m^{-3})	Comment
P 1	Pol3-1	2020/08/06 15:45:00	2020/08/19 12:43:00	8.24	9.23	7.35	8.28	11.4%	0.064	**23.2**	
P 1	Pol3-2	2020/08/06 14:26:00	2020/08/19 12:52:00	34.00	33.25	32.15	33.13	2.8%	0.064	**93.1**	
P 1	Pol3-3	2020/08/06 14:40:00	2020/08/19 12:52:00	22.22	22.66	22.54	22.47	1.0%	0.064	**63.2**	
P 1	Pol3-4	2020/08/06 14:51:00	2020/08/19 12:56:00	12.87	12.19	12.28	12.45	3.0%	0.064	**34.9**	
P 1	Pol3-5	2020/08/06 15:15:00	2020/08/19 13:00:00	6.84	7.14	6.88	6.96	2.3%	0.064	**19.5**	
P 1	Pol3-6	2020/08/06 18:02:00	2020/08/19 13:04:00	8.04	8.67	8.30	8.33	3.8%	0.064	**23.6**	
P 1	Bkd10	2020/08/06 18:02:00	2020/08/19 13:23:00	5.28	5.36	5.19	5.28	1.6%	0.064	**14.8**	
P 1	Pol4-1	2020/08/06 17:00:00	2020/08/19 13:33:00	40.10	31.82	36.33	36.08	11.5%	0.064	**102**	
P 1	Pol4-2	2020/08/06 17:07:00	2020/08/19 13:40:00	20.60	18.80	17.09	18.83	9.3%	0.064	**53.2**	
P 1	Pol4-3	2020/08/06 17:20:00	2020/08/19 13:37:00	7.82	8.02	7.38	7.74	4.2%	0.064	**21.8**	
P 2	POL3-1	2020/08/19 12:43:00	2020/09/03 13:48:00	7.68	8.08	7.94	7.90	2.6%	0.073	**19.0**	
P 2	POL3-2	2020/08/19 12:52:00	2020/09/03 14:14:00	31.96	38.21	*50.61	35.09	12.6%	0.073	**84.7**	POL3-a3 rejected
P 2	POL3-3	2020/08/19 12:52:00	2020/09/03 14:23:00	28.24	28.82	28.34	28.46	1.1%	0.073	**68.6**	
P 2	POL3-4	2020/08/19 12:56:00	2020/09/03 14:27:00	16.21	15.75	15.03	15.66	3.8%	0.073	**37.7**	
P 2	POL3-5	2020/08/19 13:00:00	2020/09/03 14:07:00	7.17	7.39	7.63	7.40	3.1%	0.073	**17.7**	
P 2	POL3-6	2020/08/19 13:04:00	2020/09/03 14:00:00	9.64	9.89	9.96	9.83	1.8%	0.073	**23.6**	
P 2	Bkd10	2020/08/19 13:23:00	2020/09/03 12:40:00	-	-	-	-	-	0.073	**-**	Missing
P 2	POL4-1	2020/08/19 13:33:00	2020/09/03 13:05:00	38.39	37.46	37.78	37.87	1.3%	0.073	**91.9**	
P 2	POL4-2	2020/08/19 13:40:00	2020/09/03 13:08:00	16.51	15.65	15.70	15.95	3.0%	0.073	**38.6**	
P 2	POL4-3	2020/08/19 13:37:00	2020/09/03 13:15:00	7.59	8.11	7.63	7.78	3.7%	0.073	**18.7**	
P 3	POL3-1	2020/09/03 13:50:00	2020/09/17 13:03:00	6.39	5.99	6.32	6.23	3.5%	0.094	**16.0**	
P 3	POL3-2	2020/09/03 14:18:00	2020/09/17 10:13:00	52.82	55.20	56.53	54.85	3.4%	0.094	**144**	
P 3	POL3-3	2020/09/03 14:24:00	2020/09/17 10:10:00	35.28	36.18	40.10	37.19	6.9%	0.094	**97.7**	
P 3	POL3-4	2020/09/03 14:35:00	2020/09/17 10:44:00	25.52	24.56	22.78	24.29	5.7%	0.094	**63.7**	
P 3	POL3-5	2020/09/03 14:08:00	2020/09/17 14:25:00	12.72	12.72	12.72	12.72	0.0%	0.094	**-**	Rejected
P 3	POL3-6	2020/09/03 14:03:00	2020/09/17 14:30:00	12.72	12.72	12.72	12.72	0.0%	0.094	**-**	Rejected
P 3	Bkd10	2020/09/03 12:42:00	2020/09/17 16:50:00	5.25	5.41	5.16	5.27	2.4%	0.094	**13.3**	
P 3	POL4-1	2020/09/03 13:06:00	2020/09/17 14:02:00	57.15	60.37	63.02	60.18	4.9%	0.094	**156**	
P 3	POL4-2	2020/09/03 13:11:00	2020/09/17 13:57:00	22.04	22.43	23.46	22.64	3.2%	0.094	**58.5**	
P 3	POL4-3	2020/09/03 13:16:00	2020/09/17 13:50:00	13.55	13.78	13.04	13.46	2.8%	0.094	**34.7**	
P 4	POL3-1	2020/09/17 13:04:00	2020/10/02 14:55:00	14.15	15.12	14.70	14.65	3.3%	0.092	**35.2**	
P 4	POL3-2	2020/09/17 10:14:00	2020/10/02 13:22:00	20.47	29.33	27.91	25.90	18.4%	0.092	**62.1**	%CV > 15%
P 4	POL3-3	2020/09/17 10:11:00	2020/10/02 13:19:00	27.76	27.67	26.02	27.15	3.6%	0.092	**65.1**	
P 4	POL3-4	2020/09/17 10:44:00	2020/10/02 12:15:00	15.48	15.59	14.71	15.26	3.1%	0.092	**36.7**	

P 4	POL3-5	2020/09/17 14:25:00	2020/10/02 15:43:00	12.20	12.24	11.94	12.13	1.3%	0.092	**29.1**	
P 4	POL3-6	2020/09/17 14:30:00	2020/10/02 15:45:00	14.62	14.16	14.67	14.48	2.0%	0.092	**34.8**	
P 4	Bkd10	2020/09/17 16:50:00	2020/10/02 18:20:00	11.13	10.09	10.18	10.47	5.5%	0.092	**25.1**	
P 4	POL4-1	2020/09/17 14:02:00	2020/10/02 14:22:00	60.98	63.09	60.14	61.40	2.5%	0.092	**145**	
P 4	POL4-2	2020/09/17 13:57:00	2020/10/02 14:19:00	22.50	21.97	21.14	21.87	3.1%	0.092	**52.8**	
P 4	POL4-3	2020/09/17 13:50:00	2020/10/02 14:16:00	14.87	14.76	16.72	15.45	7.1%	0.092	**37.3**	
P 5	POL3-1	2020/10/02 14:55:00	2020/10/14 12:14:00	9.35	9.14	9.15	9.21	1.3%	0.089	**28.0**	
P 5	POL3-2	2020/10/02 13:22:00	2020/10/14 10:27:00	17.21	16.88	17.51	17.20	1.8%	0.089	**52.5**	
P 5	POL3-3	2020/10/02 13:20:00	2020/10/14 10:25:00	13.23	13.44	13.36	13.34	0.8%	0.089	**40.6**	
P 5	POL3-4	2020/10/02 12:16:00	2020/10/14 11:11:00	8.25	8.40	9.47	8.71	7.6%	0.089	**26.3**	
P 5	POL3-5	2020/10/02 15:44:00	2020/10/14 13:30:00	15.11	16.11	14.18	15.13	6.4%	0.089	**46.0**	
P 5	POL3-6	2020/10/02 15:45:00	2020/10/14 13:33:00	17.73	20.89	19.77	19.46	8.2%	0.089	**59.3**	
P 5	Bkd 10	2020/10/02 18:20:00	2020/10/14 16:35:00	8.92	8.88	9.17	8.99	1.7%	0.089	**27.2**	
P 5	POL4-1	2020/10/02 14:23:00	2020/10/14 12:28:00	52.33	66.41	61.12	59.96	11.9%	0.089	**183**	
P 5	POL4-2	2020/10/02 14:20:00	2020/10/14 12:26:00	16.28	15.09	16.33	15.90	4.4%	0.089	**48.3**	
P 5	POL4-3	2020/10/02 14:16:00	2020/10/14 12:23:00	6.23	5.84	5.87	5.98	3.7%	0.089	**18.0**	
P 6	POL3-1	2020/10/14 12:15:00	2020/10/29 09:45:00	9.18	9.06	9.75	9.33	3.9%	0.068	**22.6**	
P 6	POL3-2	2020/10/14 10:28:00	2020/10/29 09:07:00	43.95	40.08	45.01	43.01	6.0%	0.068	**104**	
P 6	POL3-3	2020/10/14 10:25:00	2020/10/29 09:12:00	30.26	36.10	31.45	32.60	9.5%	0.068	**79.0**	
P 6	POL3-4	2020/10/14 11:11:00	2020/10/29 10:22:00	16.64	16.54	16.22	16.47	1.3%	0.068	**39.8**	
P 6	POL3-5	2020/10/14 13:30:00	2020/10/29 12:10:00	9.24	8.94	8.89	9.02	2.1%	0.068	**21.8**	
P 6	POL3-6	2020/10/14 13:33:00	2020/10/29 12:07:00	10.48	10.10	9.63	10.07	4.2%	0.068	**24.3**	
P 6	Bkd 10	2020/10/14 16:35:00	2020/10/29 08:02:00	7.08	6.89	6.71	6.89	2.6%	0.068	**16.9**	
P 6	POL4-1	2020/10/14 12:29:00	2020/10/29 11:45:00	120.10	115.35	128.15	121.20	5.3%	0.068	**294**	
P 6	POL4-2	2020/10/14 12:27:00	2020/10/29 11:42:00	41.68	40.06	37.01	39.58	6.0%	0.068	**95.9**	
P 6	POL4-3	2020/10/14 12:24:00	2020/10/29 11:40:00	15.14	16.30	16.12	15.85	3.9%	0.068	**38.3**	
P 7	POL3-1	2020/10/29 09:45:00	2020/11/11 10:08:00	4.74	4.80	4.77	4.77	0.6%	0.061	**13.2**	
P 7	POL3-2	2020/10/29 09:07:00	2020/11/11 10:23:00	39.71	37.66	39.12	38.83	2.7%	0.061	**108**	
P 7	POL3-3	2020/10/29 09:13:00	2020/11/11 10:26:00	24.83	22.54	23.13	23.50	5.1%	0.061	**65.4**	
P 7	POL3-4	2020/10/29 10:30:00	2020/11/11 10:30:00	13.99	13.90	14.83	14.24	3.6%	0.061	**39.7**	
P 7	POL3-5	2020/10/29 12:11:00	2020/11/11 12:07:00	9.26	8.27	8.27	8.60	6.7%	0.061	**23.9**	
P 7	POL3-6	2020/10/29 12:08:00	2020/11/11 12:03:00	6.53	6.90	6.48	6.64	3.5%	0.061	**18.4**	
P 7	Bkd10	2020/10/29 08:02:00	2020/11/11 08:03:00	3.13	3.23	3.05	3.14	3.0%	0.061	**8.62**	
P 7	POL4-1	2020/10/29 11:45:00	2020/11/11 13:06:00	99.12	126.85	128.36	118.11	13.9%	0.061	**329**	
P 7	POL4-2	2020/10/29 11:43:00	2020/11/11 13:03:00	37.86	36.56	36.42	36.95	2.1%	0.061	**103**	
P 7	POL4-3	2020/10/29 11:41:00	2020/11/11 12:57:00	11.91	13.41	13.44	12.92	6.8%	0.061	**35.9**	

6.3 DPAS-MANDE Monitoring: Data analysis and interpretation using 2 types of wind data

6.3.1 Background and aims

Three Directional Passive Air Samplers (DPASs) were deployed at the intensive measurement farm in order to investigate changes in airborne ammonia fluxes along downwind transects through poultry activities and a treebelt. Each DPAS had an inner carousel that was divided into 12 x 30º channels, and each channel contained a Mini Annular Denuder (MANDE) that accumulated fluxes from the relevant 30º sector. Fluxes were accumulated over approximately 2-week periods, and the DPAS-MANDE monitoring covered 4 such periods between 17 September and 11 November 2020. .

The DPAS-MANDE system is an emerging technique for ammonia monitoring, and this was the first time it had been deployed at a "real world" intensive agriculture site. The deployment was therefore a pilot study, and an opportunity to compare DPAS-MANDE results with established techniques like ALPHA samplers and automatic monitors. For these comparisons, an ALPHA sampler was deployed beside each DPAS-MANDE sampler, and 2 of the DPAS-MANDE samplers were located alongside automatic monitors.

Data on wind speed and direction are needed to interpret the fluxes obtained from DPAS-MANDE samplers. Specifically, wind data are needed to determine the duration and volume of the airflows that advected the collected ammonia into each directional channel, so that concentrations and fluxes can be evaluated for each 30º sector and period. 2 types of wind data were available: (i) measurements made at 2 automatic monitoring stations located on either side of the tree belt, and (ii) modelled data from numerical weather prediction (NWP). DPAS-MANDE results were evaluated separately for both types of data, in order to compare results based on measured and modelled winds.

The broad aims of the DPAS-MANDE investigations were to:

(i) Compare DPAS-MANDE data with co-located ALPHA and automatic measurements.
(ii) Determine if DPAS-MANDE samplers can resolve ammonia from poultry activities, by sampling upwind and downwind of them.
(iii) Infer how much ammonia is reduced by tree,s by comparing DPAS-MANDE results before and after the wind crossed a treebelt.
(iv) Compare ammonia reductions based on measured and modelled wind data.
(v) Explore the capabilities/limitations of DPAS-MANDE samplers, and to identify improvements.

The comparisons of DPAS-MANDE data with ALPHA and automatic measurements showed that the samplers gave anomalous data for some sectors and periods when the speed and/or duration of wind was low. The data from these wind conditions were "screened out" so that only more robust "screened in" data were used to evaluate ammonia reductions by trees. A further aim of the investigations was therefore to develop and apply criteria for screening out anomalous data, and to identify their cause so that improvements to the DPAS-MANDE design could be recommended to prevent anomalies in future.

6.3.2 Geographical setting

Figure 6.3.1 shows the neighbourhood of the intensive measurements farm (upper right) and another intensive poultry farm (lower left) that lies about 0.5km away in the direction of the prevailing south-west wind. The farms are surrounded by fields of (sheep) pasture and there are treebelts to the north-east of each farm i.e. in a prevailing downwind direction. The 3 DPAS-MANDE samplers were deployed at the intensive measurement farm along a transect that was aligned with the prevailing wind and with the long-axis of a rectangular poultry shed. This shed housed 6000 birds, but the other intensive poultry farm had a shed housing 32,000 birds.

Figure 6.3.1. Neighbourhood of intensive measurement farm (upper right) showing positions of 3 DPAS-MANDE samplers, and of another intensive poultry farm (bottom left).

Figure 6.3.2 shows the intensive measurements farm in more detail. The shed with 6000 birds has an adjoining ranging area to the south-east, and a treebelt that is 25m wide to the north-east. There are 2 other poultry sheds on the farm, containing 7,000 and 16,000 birds, which could potentially emit ammonia, but the directional basis of the DPAS-MANDE sampling was used to focus on winds aligned with the shed housing 6,000 birds, and to exclude any ammonia from the 2 other sheds. The ability of the DPAS-MANDE sampler to resolve ammonia from different directional sectors is an advantage in this multi-shed situation e.g. compared to ALPHA samplers which collect from all sectors.

Figure 6.3.2. Intensive measurements farm showing positions of poultry sheds, 3 DPASs, ranging area and 25m tree belt.

6.3.3 Approach

DPAS data were analysed and interpreted in 5 stages:

a) Wind data from different sources were collated for individual periods and 30º sectors.
b) DPAS-based concentrations were calculated using wind data and sampled ammonia masses, and were compared with corresponding concentrations from automatic monitoring.
c) The comparisons were used to develop criteria for screening DPAS measurements, so that anomalous results due to short-duration samples and light winds could be "screened-out", and more robust results for evaluating ammonia reduction by trees could be "screened in".
d) The "screened in" DPAS measurements were used to calculate concentrations and fluxes for different locations, periods and sectors.
e) The "screened-in" concentrations and fluxes were used to evaluate ammonia reduction by trees.

Sections 6.3.2-7 below give details of stages (a)-(e) respectively. Section 8 summarises and discusses the main points from DPAS investigations.

6.3.4 Collation of wind data

Wind speed and direction were measured by the UK Centre for Ecology and Hydrology (UKCEH) at a "Before Trees" position (near DPAS 2 in Figure 2) using a sonic anemometer at 2.3m above ground. They were also measured by the Environment Agency (EA) at an "After Trees" position (near DPAS 3 in Figure 2) with a conventional anemometer and vane at 8m above ground. Further wind speed and direction data were available from Numerical Weather Prediction (NWP) for the grid-square containing the intensive measurements farm, based on a reference height of 10m above ground.

DPAS-MANDE samplers have the advantage of not needing power, which simplifies fieldwork e.g. their locations are unconstrained by the availability of power supplies. But they do need wind speed and direction data for evaluating pollutant fluxes and concentrations, and if these data are measured by automatic instruments there may still be a need for power. However, if suitable wind data are available from NWP there is again no need for power and the advantage of power-free fieldwork is maintained.

Wind speed data were collated and compared for all 3 data sources: UKCEH, EA and NWP. This was done in order to assess the most appropriate source and reference height for evaluating DPAS-MANDE samples, as discussed in this section. It was also done in order to assess whether or not NWP data could be used reliably to evaluate ammonia reduction by trees, instead of measured data, as discussed in this section and section 6.3.7.

For each source of wind data (UKCEH, EA, NWP), Table 1 shows the reference height above ground and the average wind-speed in each sampling period. The heights of the EA and NWP data are similar, and exceed the height of the UKCEH data i.e. 8m and 10m v. 2.3m. The effect of the different heights is shown by the average wind speeds of the EA and NWP data, which are approximately 3 times those of the UKCEH data.

The airflows into DPAS sampling channels in each period were estimated initially with UKCEH wind data. These estimates were then used to calculate DPAS-based ammonia concentrations. The UKCEH wind data were chosen because their height above ground (2.3.m) was nearest to that of the DPAS inlet (1.2m), and because they covered all 4 periods (by contrast, EA wind data were only available for 2 periods).

NWP wind data also covered all 4 period. They were also used to estimate DPAS airflows and concentrations, so that results based on NWP data could be compared with those based on UKCEH data. Before using the NWP data, they were adjusted to account for the higher wind speeds at their reference height (10m) compared to the UKCEH reference height (2.3m). Table 6.3.1 shows the ratios of the average wind speeds from UKCEH, NWP and EA data in each period. The wind speeds for NWP and EA data were similar (within 20%). But they were about 3 times those for UKCEH data, which is consistent with the greater reference heights of NWP and EA data (10m and ~8m respectively v. 2.3m for UKCEH data. The ratios of UKCEH to NWP data in each period were used to decelerate the NWP wind speeds so they matched those from UKCEH data. The wind speeds of NWP data were therefore adjusted to the same height as the UKCEH data; but the durations of NWP winds from each sector were not adjusted.

Table 6.3.1 Average wind speeds from measurements & Numerical Weather Prediction for Periods 1-4

Period			Average wind speed m/s			Ratios of Wind Speeds		
No.	Dates (2020)	Hours	UKCEH	EA	NWP	EA: UKCEH	NWP: UKCEH	NWP: EA
			(a)	(b)	(c)			
1	17/9-2/10	360	1.15	3.61	2.88	3.14	2.50	0.80
2	2-14/10	288	1.20	4.68	3.70	3.90	3.08	0.83
3	10-29/10	360	1.08	n/a	3.77	n/a	3.49	n/a
4	29/10-11/11	312	1.28	n/a	3.55	n/a	2.77	n/a

(a) UK Centre for Ecology & Hydrology (UKCEH) sonic anemometer was at "Before Trees" position and 2.3m above ground level.
(b) Environment Agency (EA) conventional wind monitor was at "After Trees" position and ~8m above ground level.
(c) Numerical Weather Prediction (NWP) data were for local grid square, referenced to 10m above ground level.

Table 6.3.2. Wind data for 30^o sectors from UKCEH measurements & Numerical Weather Prediction

30^o Sector	Data Source	Period 1			Period 2			Period 3			Period 4		
		hrs	Spd. m/s	Vol. m^3	hrs	Spd. m/s	Vol. m^3	hrs	Spd. m/s	Vol. m^3	hrs	Spd. m/s	Vol. m^3
355-025	UKCEH	18.0	1.00	0.0509	18.5	1.27	0.0668	11.5	0.61	0.0198	2.4	0.43	0.0029
	NWP	*22.2*	*1.25*	*0.0785*	*17.1*	*1.39*	*0.0672*	*13.0*	*0.78*	*0.0287*	*0.0*	*0.00*	*0.0000*
025-055	UKCEH	9.8	0.90	0.0249	15.1	1.47	0.0628	19.9	0.96	0.0543	2.9	0.31	0.0026
	NWP	*4.0*	*0.83*	*0.0094*	*15.1*	*1.27*	*0.0542*	*25.1*	*0.95*	*0.0674*	*0.0*	*0.00*	*0.0000*
055-085	UKCEH	9.2	0.91	0.0237	6.0	1.13	0.0192	2.5	0.66	0.0047	3.5	0.43	0.0043
	NWP	*10.1*	*0.58*	*0.0166*	*5.0*	*1.23*	*0.0174*	*7.0*	*0.86*	*0.0170*	*1.0*	*0.41*	*0.0012*
085-115	UKCEH	15.9	1.01	0.0454	7.5	0.74	0.0157	6.0	0.76	0.0129	8.3	0.63	0.0147
	NWP	*15.2*	*0.68*	*0.0292*	*8.1*	*0.58*	*0.0133*	*6.0*	*0.72*	*0.0122*	*6.1*	*0.65*	*0.0112*
115-145	UKCEH	52.9	1.56	0.2319	13.5	0.92	0.0351	25.4	1.34	0.0966	37.2	1.40	0.1471
	NWP	*54.6*	*0.91*	*0.1405*	*14.1*	*0.60*	*0.0239*	*18.1*	*0.97*	*0.0496*	*60.0*	*0.98*	*0.1663*
145-175	UKCEH	24.7	1.40	0.0978	6.0	0.95	0.0161	51.9	1.31	0.1926	59.6	1.57	0.2645
	NWP	*64.7*	*1.25*	*0.2287*	*8.1*	*0.61*	*0.0149*	*64.2*	*1.20*	*0.2179*	*81.3*	*1.39*	*0.3196*
175-205	UKCEH	30.0	1.02	0.0874	4.5	0.95	0.0121	67.8	1.00	0.1923	38.9	0.88	0.0969
	NWP	*15.2*	*1.41*	*0.0606*	*9.1*	*0.73*	*0.0188*	*75.2*	*1.16*	*0.2467*	*30.5*	*1.44*	*0.1242*
205-235	UKCEH	42.6	1.11	0.1337	12.0	1.09	0.0370	63.3	1.44	0.2586	57.8	2.18	0.3563
	NWP	*23.3*	*0.85*	*0.0560*	*6.0*	*0.93*	*0.0158*	*50.1*	*1.23*	*0.1743*	*32.5*	*1.85*	*0.1700*
235-265	UKCEH	27.7	0.70	0.0548	26.1	0.84	0.0620	48.9	1.03	0.1427	50.1	1.08	0.1531
	NWP	*20.2*	*0.67*	*0.0383*	*19.1*	*0.94*	*0.0508*	*40.1*	*1.19*	*0.1349*	*49.8*	*1.39*	*0.1957*
265-295	UKCEH	27.2	0.67	0.0515	58.7	1.09	0.1809	24.9	0.72	0.0509	27.1	0.59	0.0453
	NWP	*28.3*	*0.91*	*0.0728*	*57.4*	*1.53*	*0.2483*	*22.1*	*1.42*	*0.0887*	*32.5*	*1.01*	*0.0928*
295-325	UKCEH	64.2	1.43	0.2596	97.8	1.47	0.4065	17.5	0.83	0.0411	14.7	0.89	0.0371
	NWP	*54.6*	*1.42*	*0.2192*	*89.6*	*1.35*	*0.3421*	*7.0*	*0.46*	*0.0091*	*16.3*	*1.00*	*0.0461*
325-355	UKCEH	37.5	1.03	0.1092	22.1	1.05	0.0656	20.4	0.66	0.0383	9.4	0.25	0.0067
	NWP	*47.5*	*1.53*	*0.2055*	*39.3*	*1.01*	*0.1122*	*32.1*	*0.57*	*0.0517*	*2.0*	*0.85*	*0.0048*
All (a)	UKCEH	360	1.15	*1.1708*	288	1.20	0.9798	360	1.08	1.1048	312	1.28	*1.1315*
	NWP	*360*	*1.14*	*1.1553*	*288*	*1.20*	*0.9780*	*360*	*1.08*	*1.0982*	*312*	*1.28*	*1.1319*

UKCEH data in ordinary type. NWP) data in italics. NWP speeds have been adjusted (reduced) by the ratio of average UKCEH and NWP speeds in each period. Shaded periods/sectors have "screened-in" data, for which: duration >= 24 hrs; speed >= 1.0 m/s; volume >= 0.0678 m^3.
(a) Values for each period are totals of duration (hours) and volume (m^3), and averages of wind speed (m/s).

Table 6.3.2 shows the duration and average speed of the wind for each 30^o sector and Period, based on monitoring (by UKCEH) and on Numerical Weather Prediction (NWP). For the NWP data, the speeds have been adjusted (reduced) by the ratio of the overall UKCEH and NWP speeds for the relevant period, as shown in Table 6.3.1; but at the durations are unadjusted.

Table 6.3.2 also shows the corresponding volumes of air that entered the 1mm-diameter orifice of the MANDE in each DPAS channel during each Period. The volumes were calculated from the relevant duration and average speed of wind, and by assuming that the airspeed through the orifice equalled the ambient wind speed. Table 6.3.2 also shows the average wind speed across all 30^o sectors in each Period for both UKCEH and NWP data, these speeds were the same (within rounding) because the overall NWP wind speed was reduced to match the overall UKCEH speed. Similarly, Table 6.3.2 shows the total volume of air that entered all 12 orifices in each period, which were also the same (within rounding) for both UKCEH and NWP data.

6.3.5 Comparison of concentrations based on DPAS-MANDE sampling and automatic data

Ammonia concentrations were evaluated from DPAS-MANDE samples by dividing: (i) the mass of ammonia collected in a given sector and period, by (ii) the volume of air that entered the MANDE orifice in that sector and period (based on the speed and duration of the airflow from Table 6.3.2). Concentration data based on DPAS sampling and automatic measurements were available from the "Before Trees" and "After Trees" positions for Period 1. But both types of data were only available from the "Before Trees" position for period 2, because the alignment of the DPAS carousel at the "After Trees" position was altered by strong winds during Period 2. Also, automatic data were unavailable for Periods 3 and 4 because of issues with power supplies.

6.3.6 Comparisons based on UKCEH wind data

Table 6.3.3 shows the average concentrations that are available for comparing DPAS and automatic measurements for 30º sectors, based on UKCEH wind data. The DPAS-MANDE results are based on the ammonia masses collected by MANDEs, and on the airflow volumes measured by the UKCEH sonic anemometer as shown in Table 6.3.2

The automatic concentrations are based on measurements by UKCEH AIRmonnia instruments.

The DPAS-MANDE and automatic data show some periods and sectors when concentrations from both methods are in broad agreement (e.g. within a factor of 2), but others when they differ markedly (e.g. by up to a factor of 10. The periods and sectors with broad agreement tend to have longer durations of wind (e.g. >24 hours) and higher average wind speeds (e.g. >1 m/s). During these periods and sectors, the evaluated volumes of airflow through the MANDE orifice are also larger (e.g. > 0.0678 m^3, which corresponds to 24 hours of airflow at 1 m/s through a 1mm diameter orifice). There are 14 periods and sectors with these higher durations, speeds and volumes, and they are shaded in Table 6.3.3. For these periods and sectors the average ammonia concentrations were 51.2 and 51.6 µg/m^3 from automatic and DPAS data respectively, and the two types of data were weakly correlated (r = 0.40).
In Table 6.3.3 there are 22 periods and sectors with lower durations, speeds and volumes of wind, which are unshaded. For these periods and sectors the average ammonia concentrations were 57.1 and 248.9 µg/m^3 from automatic and DPAS-MANDE data respectively, and the two types of concentration data were uncorrelated. Also for these periods and sectors it was noticeable that relatively large masses of ammonia were collected during periods with relatively low average wind speeds, even though the duration of wind and the volume of airflow were low (e.g. Sector 085-115º at the "Before Trees" position in period 2). Such combinations of large collected masses with low durations and volumes of wind gave anomalously high DPAS concentrations (e.g. 710.8 µg/m^3 for Sector 085-115º at the "Before Trees" position in period 2).

Table 6.3.3. Ammonia concentrations available for comparing DPAS-MANDE data (based on UKCEH wind) with automatic data

30º Sector	Period 1						Period 2					
	Hrs	WS	Vol.	Mass	Conc.	*Auto*	Hrs	WS	Vol.	Mass	Conc.	*Auto*
	(a)	(a)	(b)				(a)	(a)	(b)			
	hrs	m/s	m^3	µg	µg/m^3	µg/m^3	hrs	m/s	m^3	µg	µg/m^3	µg/m^3
	Before Trees											

355-025	18.0	1.00	0.0509	8.67	170.3	*30.0*	18.6	1.27	0.0668	8.33	124.7	*50.6*
025-055	9.8	0.90	0.0249	7.78	312.4	*39.4*	15.1	1.47	0.0628	8.12	129.3	*53.3*
055-085	9.2	0.91	0.0237	8.58	362.0	*36.7*	6.0	1.13	0.0192	8.26	430.2	*78.2*
085-115	15.9	1.01	0.0454	7.44	163.9	*34.3*	7.5	0.74	0.0157	11.16	710.8	*58.4*
115-145	52.9	1.55	0.2319	9.45	40.8	*30.4*	13.5	0.92	0.0351	5.12	145.9	*59.4*
145-175	24.7	1.40	0.0978	9.60	98.2	*40.8*	6.0	0.95	0.0161	10.46	649.7	*67.6*
175-205	30.0	1.02	0.0874	9.29	106.3	*94.5*	4.5	0.95	0.0121	10.43	861.9	*101.4*
205-235	42.6	1.11	0.1337	10.19	76.2	*120.3*	12.0	1.09	0.0370	5.09	137.6	*123.4*
235-265	27.7	0.70	0.0548	10.19	185.9	*114.7*	26.1	0.84	0.0620	4.56	73.5	*87.9*
265-295	27.2	0.67	0.0515	6.70	130.1	*80.7*	58.7	1.09	0.1809	4.05	22.4	*59.7*
295-325	64.2	1.43	0.2596	9.07	35.0	*43.2*	97.8	1.47	0.4065	10.10	24.8	*56.2*
325-355	37.5	1.03	0.1092	11.89	108.9	*36.4*	22.1	1.05	0.0656	9.24	140.9	*51.0*
	After trees											
355-025	18.0	1.00	0.0509	4.49	88.2	*13.4*						
025-055	9.8	0.90	0.0249	4.56	183.1	*15.4*						
055-085	9.2	0.91	0.0237	4.93	208.0	*20.6*						
085-115	15.9	1.01	0.0454	3.34	73.6	*18.5*						
115-145	52.9	1.55	0.2319	3.47	15.0	*19.2*						
145-175	24.7	1.40	0.0978	4.08	41.7	*27.3*						
175-205	30.0	1.02	0.0874	3.72	42.6	*52.1*						
205-235	42.6	1.11	0.1337	6.84	51.2	*94.8*						
235-265	27.7	0.70	0.0548	4.69	85.6	*77.3*						
265-295	27.2	0.67	0.0515	5.58	108.3	*44.9*						
295-325	64.2	1.43	0.2596	5.49	21.1	*27.7*						
325-355	37.5	1.03	0.1092	4.13	37.8	*14.3*						

Shaded periods/sectors have "screened-in" data, for which: duration >= 24 hrs; speed >= 1.0 m/s; volume >= 0.0678 m^3.
(a) based on UKCEH wind measurements at "Before Trees" position, as in Table 2.
(b) based on UKCEH wind measurements, and assuming air speed through MANDE orifice = external wind speed.

The anomalously high concentrations from periods and sectors with low durations, speeds and volumes, probably occurred because the wind speed was insufficient to align the DPAS's air inlet, which meant it did not face upwind. This non-alignment would have allowed the light ambient wind to enter the open "downwind" end of the MANDE i.e. to enter it as a "backflow" without being restricted by the 1mm orifice. Such "backflows" would introduce ammonia to the MANDE through a much larger area (i.e. via an aperture of diameter ~8mm instead of 1mm) so that relatively large, and anomalous, masses of ammonia could be collected from short durations of exposure.

6.3.7 Comparisons based on NWP wind data

The comparison of ammonia concentrations from DPAS and automatic data was repeated using DPAS-MANDE concentrations based on NWP wind data, as shown in Table 6.3.4. There were 9 periods and sectors when the duration, speed and volume of airflows based on NWP wind data exceeded 24 hours, 1.00 m/s and 0.0678 m^3 respectively i.e. they exceeded the same values as for "screened in" UKCEH wind data. These 9 periods and sectors are shaded in Table 6.3.4, and their average concentrations from automatic and DPAS data were similar i.e. 39.6 and 36.9 $\mu g/m^3$, respectively. However, there were 27 Periods and Sectors with lower durations, speeds and volumes, and their average concentrations from automatic and DPAS data were markedly different i.e. 59.9 and 271.0 $\mu g/m^3$, respectively. This suggested that anomalously high concentrations due to "backflows" that happened when the duration, speed and volume of wind were low, were an issue when NWP wind data were used, as well as when UKCEH wind measurements were used.

Table 6.3.4. Ammonia concentrations available for comparing DPAS-MANDE data (based on NWP wind) with automatic data.

30° Sector	Period 1						Period 2					
	Hrs	WS	Vol.	Mass	Conc.	*Auto*	Hrs	WS	Vol.	Mass	Conc.	*Auto*
	(a)	(a)	(b)				(a)	(a)	(b)			
	hrs	m/s	m^3	µg	µg/m^3	µg/m^3	hrs	m/s	m^3	µg	µg/m^3	µg/m^3
	Before Trees											
355-025	22.2	1.25	0.0785	8.67	110.4	*30.0*	17.1	1.39	0.0672	8.33	124.0	*50.6*
025-055	4.0	0.83	0.0094	7.78	827.7	*39.4*	15.1	1.27	0.0542	8.12	149.8	*53.3*
055-085	10.1	0.58	0.0166	8.58	516.9	*36.7*	5.0	1.23	0.0174	8.26	474.7	*78.2*
085-115	15.2	0.68	0.0292	7.44	254.8	*34.3*	8.1	0.58	0.0133	11.16	839.1	*58.4*
115-145	54.6	0.91	0.1405	9.45	37.3	*30.4*	14.1	0.60	0.0239	5.12	214.2	*59.4*
145-175	64.7	1.25	0.2287	9.60	42.0	*40.8*	8.1	0.61	0.0140	10.46	747.1	*67.6*
175-205	15.2	1.41	0.0606	9.29	153.3	*94.5*	9.1	0.73	0.0188	10.43	554.8	*101.4*
205-235	23.3	0.85	0.0560	10.19	182.0	*120.3*	6.0	0.93	0.0158	5.09	322.2	*123.4*
235-265	20.2	0.67	0.0383	10.19	266.1	*114.7*	19.1	0.94	0.0508	4.56	89.8	*87.9*
265-295	28.3	0.91	0.0728	6.70	92.0	*80.7*	57.4	1.53	0.2483	4.05	16.3	*59.7*
295-325	54.6	1.42	0.2192	9.07	41.4	*43.2*	89.6	1.35	0.3421	10.10	29.5	*56.2*
325-355	47.5	1.53	0.2055	11.89	57.9	*36.4*	39.3	1.01	0.1122	9.24	82.4	*51.0*
	After trees											
355-025	22.2	1.25	0.0785	4.49	57.2	*13.4*						
025-055	4.0	0.83	0.0094	4.56	485.1	*15.4*						
055-085	10.1	0.58	0.0166	4.93	297.0	*20.6*						
085-115	15.2	0.68	0.0292	3.34	114.4	*18.5*						
115-145	54.6	0.91	0.1405	3.47	24.7	*19.2*						
145-175	64.7	1.25	0.2287	4.08	17.8	*27.3*						
175-205	15.2	1.41	0.0606	3.72	61.4	*52.1*						
205-235	23.3	0.85	0.0560	6.84	122.1	*94.8*						
235-265	20.2	0.67	0.0383	4.69	122.5	*77.3*						
265-295	28.3	0.91	0.0728	5.58	76.6	*44.9*						
295-325	54.6	1.42	0.2192	5.49	25.0	*27.7*						
325-355	47.5	1.53	0.2055	4.13	20.1	*14.3*						

Shaded periods/sectors have "screened-in" data, for which: duration >= 24 hrs; speed >= 1.0 m/s; volume >= 0.0678 m^3.
(a) based on NWP wind data adjusted to average speed of UKCEH wind at "Before Trees" position, as in Table 2.
(b) based on NWP UKCEH wind measurements, and assuming air speed through MANDE orifice = external wind speed.

6.3.8 Screening criteria for DPAS-MANDE data

Section 3 has shown that DPAS-MANDE concentrations for periods and sectors with moderate or greater amounts of wind were broadly consistent with concentrations from automatic measurements. This consistency supports the assumption that air flowed through the MANDE's 1 mm orifice at a similar speed to the external wind, and that all of the ammonia in that air was collected. Criteria were developed to "screen in" these periods and sectors so that their DPAS data could be used to evaluate ammonia reduction by trees. Specifically, Periods and Sectors were "screened in" if they had winds for more than 24 hours at an average speed exceeding 1 m/s, and if the associated volume of air through a 1mm orifice exceeded 0.0678 m^3 (this volume corresponds to 24 hours of wind at x 1 m/s through a 1mm orifice). Periods and sectors that did not meet all these criteria were "screened out" and not used to evaluate ammonia reduction by trees.

The periods and sectors that were "screened in" are shaded in Table 6.3.1 for both UKCEH (measured) winds and NWP (modelled) winds. There are 17 "screened in" periods and sectors for UKCEH winds, and 15 for NWP winds. The number of periods and sectors available to evaluate ammonia reduction by trees was also limited by two other factors:

* There were no data from the "After Trees" position in period 2, due to the high wind speeds that altered the orientation of the DPAS carousel (as explained above); so "screened-in" data were only available at "After Trees" position for periods 1, 3 and 4.

* A few of the periods and sectors with "screened in" data were not aligned with the relevant directions for evaluating ammonia reduction by trees e.g. they did not include directions of airflow from the poultry shed to the treebelt.

After taking account of all these factors, the number of sectors and periods with wind data available for evaluating ammonia reduction by trees from DPAS measurements was 13 for UKCEH wind data, and 9 for NWP data. The data for sectors and periods are shown in Tables 6.3.5 and 6.3.6, respectively.

Table 6.3.5 DPAS-MANDE monitoring periods & sectors available for evaluating ammonia reduction by trees using UKCEH wind data

30° Sector	Period 1			Period 3			Period 4		
	hrs	Speed	Volume	hrs	Speed	Volume	hrs	Speed	Volume
		m/s	m^3		m/s	m^3		m/s	m^3
115-145	52.9	1.56	0.2319	25.4	1.34	0.0966	37.2	1.40	0.1471
145-175	24.7	1.40	0.0978	51.9	1.31	0.1926	59.6	1.57	0.2645
175-205	30.0	1.02	0.0874	67.8	1.00	0.1923	-	-	-
205-235	42.6	1.11	0.1337	63.3	1.44	0.2586	57.8	2.18	0.3563
235-265	-	-	-	48.9	1.03	0.1427	50.1	1.08	0.1531

Table 6.3.6 DPAS-MANDE monitoring periods & sectors available to evaluate ammonia reduction by trees using NWP wind data

30° Sector	Period 1			Period 3			Period 4		
	hrs	Speed	Volume	hrs	Speed	Volume	hrs	Speed	Volume
		m/s	m^3		m/s	m^3		m/s	m^3
145-175	64.7	1.25	0.2287	64.2	1.20	0.2179	81.3	1.39	0.3196
175-205	-	-	-	75.2	1.16	0.2467	30.5	1.44	0.1242
205-235	-	-	-	50.1	1.23	0.1743	32.5	1.85	0.1700
235-265	-	-	-	40.1	1.19	0.1349	49.8	1.39	0.1957

The DPAS-MANDE investigations at the intensive measurements farm were focussed on the shed that contained 6000 organic birds, as shown in Figure 6.3.2. These poultry were kept in the shed at night, but were admitted to the ranging area beside the shed during daytime. Because the "screened-in" data were for periods and sectors with at least 24 hours of wind, the corresponding DPAS-MANDE measurements were likely to include a mixture of night-time and daytime conditions. It follows that the evaluated amounts of ammonia reduction by trees are likely to cover a full range of ammonia emissions, rather than being restricted to night-time (shed) or daytime (ranging area) emissions only.

6.3.9 Concentrations and fluxes for "screened-in" DPAS-MANDE data

Data available

The “screened-in” DPAS-MANDE data were available at the intensive measurements farm for Periods 1, 3 and 4. These data were used to calculate ammonia concentrations and fluxes when the wind blew from the 6000 -bird shed towards and through the treebelt. Concentrations and fluxes were calculated at 3 positions, as shown in Figure 6.3.2:

- “Upwind”: ~50 m before the wind had reached the shed or ranging area
- “Before Trees: ~25m after wind had crossed the shed or ranging area, but before it reached the treebelt.
- “After Trees”: ~50 m downwind of the shed or ranging area, after the wind had crossed the treebelt.

Concentrations and fluxes were calculated separately using UKCEH and NWP wind data, so that the effect of using different wind data could be investigated. DPAS concentrations and fluxes available using UKCEH wind data are shown in Tables 6.3.7 and 6.3.8 respectively, and those available using NWP data are shown in Tables 6.3.9 and 6.3.10 respectively.

Table 6.3.7. DPAS-MANDE concentrations for evaluating reduction by trees using UKCEH wind data

30° Sector	Period 1						Period 3					Period 4				
	Hrs	W.S.	Vol.	NH_3 Mass	Concentration		Hrs.	W.S.	Vol.	NH_3 Mass	Conc.	Hrs.	W.S.	Vol.	NH_3 Mass	Conc.
					DPAS	Auto										
	hrs	m/s	m^3	µg	µg/m^3		hrs	m/s	m^3	µg	µg/m^3	hrs	m/s	m^3	µg	µg/m^3
	“Upwind” Position															
115-145	52.9	1.56	0.2319	5.24	22.6	-	25.4	1.34	0.0966	5.83	60.4	37.2	1.40	0.1471	0.86	5.8
145-175	24.7	1.40	0.0978	4.46	45.6	-	51.9	1.31	0.1926	6.99	36.3	59.6	1.57	0.2645	1.38	5.2
175-205	30.0	1.02	0.0874	2.92	33.4	-	67.8	1.00	0.1923	3.44	17.9	-	-	-	-	-
205-235	42.6	1.11	0.1337	3.46	25.9	-	63.3	1.44	0.2586	3.51	13.6	57.8	2.18	0.3563	3.97	11.1
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	3.23	22.6	50.1	1.08	0.1531	1.97	12.9
	“Before Trees” Position															
115-145	52.9	1.56	0.2319	9.45	40.8	*30.4*	25.4	1.34	0.0966	21.1	218.4	37.2	1.40	0.1471	12.46	84.7
145-175	24.7	1.40	0.0978	9.60	98.2	*40.8*	51.9	1.31	0.1926	16.1	83.6	59.6	1.57	0.2645	20.61	77.9
175-205	30.0	1.02	0.0874	9.29	106.3	*94.5*	67.8	1.00	0.1923	15.5	80.6	-	-	-	-	-
205-235	42.6	1.11	0.1337	10.19	76.2	*120.3*	63.3	1.44	0.2586	18.3	70.8	57.8	2.18	0.3563	11.44	32.1
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	14.8	103.7	50.1	1.08	0.1531	14.40	94.1
	“After Trees” Position															
115-145	52.9	1.56	0.2319	3.47	15.0	*19.2*	25.4	1.34	0.0966	2.31	23.9	37.2	1.40	0.1471	3.14	21.3
145-175	24.7	1.40	0.0978	4.08	41.7	*27.3*	51.9	1.31	0.1926	3.84	19.9	59.6	1.57	0.2645	4.49	17.0
175-205	30.0	1.02	0.0874	3.72	42.6	*52.1*	67.8	1.00	0.1923	4.03	21.0	-	-	-	-	-
205-235	42.6	1.11	0.1337	6.84	51.2	*94.8*	63.3	1.44	0.2586	8.66	33.5	57.8	2.18	0.3563	13.97	39.2
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	8.80	61.7	50.1	1.08	0.1531	12.83	83.8

Table 6.3.8. DPAS-MANDE fluxes for evaluating reduction by trees using UKCEH wind data

30° Sector	Period 1						Period 3					Period 4				
	Hrs	W.S.	Vol.	NH_3 Mass	Flux		Hrs.	W.S.	Vol.	NH_3 Mass	Flux.	Hrs.	W.S.	Vol.	NH_3 Mass	Flux
					DPAS	*Auto*					µg/m^2/s					µg/m^2/s
	hrs	m/s	m^3	µg	µg/m^2/s		hrs	m/s	m^3	µg		hrs	m/s	m^3	µg	
	“Upwind” Position															
115-145	52.9	1.56	0.2319	5.24	35.0	-	25.4	1.34	0.0966	5.83	81.2	37.2	1.40	0.1471	0.86	8.2
145-175	24.7	1.40	0.0978	4.46	63.9	-	51.9	1.31	0.1926	6.99	47.6	59.6	1.57	0.2645	1.38	8.2
175-205	30.0	1.02	0.0874	2.92	34.4	-	67.8	1.00	0.1923	3.44	17.9	-	-	-	-	-
205-235	42.6	1.11	0.1337	3.46	28.7	-	63.3	1.44	0.2586	3.51	19.6	57.8	2.18	0.3563	3.97	24.3
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	3.23	23.4	50.1	1.08	0.1531	1.97	13.9
	“Before Trees” Position															
115-145	52.9	1.56	0.2319	9.45	63.2	*47.4*	25.4	1.34	0.0966	21.1	293.8	37.2	1.40	0.1471	12.46	118.4
145-175	24.7	1.40	0.0978	9.60	98.2	*29.1*	51.9	1.31	0.1926	16.1	109.7	59.6	1.57	0.2645	20.61	122.3
175-205	30.0	1.02	0.0874	9.29	113.2	*67.5*	67.8	1.00	0.1923	15.5	80.8	-	-	-	-	-

205-235	42.6	1.11	0.1337	10.19	84.5	108.4	63.3	1.44	0.2586	18.3	102.2	57.8	2.18	0.3563	11.44	70.0
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	14.8	107.0	50.1	1.08	0.1531	14.40	101.6
	"After Trees" Position															
115-145	52.9	1.56	0.2319	3.47	23.2	12.3	25.4	1.34	0.0966	2.31	32.2	37.2	1.40	0.1471	3.14	29.8
145-175	24.7	1.40	0.0978	4.08	58.4	19.5	51.9	1.31	0.1926	3.84	26.2	59.6	1.57	0.2645	4.49	26.6
175-205	30.0	1.02	0.0874	3.72	43.9	51.1	67.8	1.00	0.1923	4.03	21.0	-	-	-	-	-
205-235	42.6	1.11	0.1337	6.84	56.8	85.4	63.3	1.44	0.2586	8.66	48.4	57.8	2.18	0.3563	13.97	85.5
235-265	-	-	-	-	-	-	48.9	1.03	0.1427	8.80	63.6	50.1	1.08	0.1531	12.83	90.6

Table 6.3.9. DPAS-MANDE concentrations for evaluating reduction by trees using NWP wind data

30º Sector	Period 1						Period 3					Period 4				
	Hrs	W.S.	Vol.	NH_3 Mass	Concentration		Hrs.	W.S.	Vol.	NH_3 Mass	Conc.	Hrs.	W.S.	Vol.	NH_3 Mass	Conc.
					DPAS	Auto										
	hrs	m/s	m³	µg	µg/m³		hrs	m/s	m³	µg	µg/m³	hrs	m/s	m³	µg	µg/m³
	"Upwind" Position															
145-175	64.7	1.25	0.2287	4.46	19.5	-	64.2	1.20	0.2179	6.99	32.1	81.3	1.39	0.3196	1.38	4.3
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	3.44	13.9	30.5	1.44	0.1242	0.95	7.6
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	3.51	20.1	32.5	1.85	0.1700	3.97	23.4
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	3.23	23.9	49.8	1.39	0.1957	1.97	10.1
	"Before Trees" Position															
145-175	64.7	1.25	0.2287	9.60	42.0	40.8	64.2	1.20	0.2179	16.1	73.9	81.3	1.39	0.3196	20.61	64.5
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	15.5	80.6	30.5	1.44	0.1242	19.53	157.2
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	18.3	62.8	32.5	1.85	0.1700	11.44	67.3
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	14.8	109.7	49.8	1.39	0.1957	14.40	73.6
	"After Trees" Position															
145-175	64.7	1.25	0.2287	4.08	17.8	27.3	64.2	1.20	0.2179	3.84	17.6	81.3	1.39	0.3196	4.49	14.0
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	4.03	16.3	30.5	1.44	0.1242	8.64	69.6
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	8.66	49.7	32.5	1.85	0.1700	13.97	82.2
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	8.80	65.2	49.8	1.39	0.1957	12.83	65.6

Table 6.3.10. DPAS-MANDE fluxes for evaluating reduction by trees using NWP wind data

30º Sector	Period 1						Period 3					Period 4				
	Hrs	W.S.	Vol.	NH_3 Mass	Flux		Hrs.	W.S.	Vol.	NH_3 Mass	Flux.	Hrs.	W.S.	Vol.	NH_3 Mass	Flux
					DPAS	Auto					µg/m²/s					µg/m²/s
	hrs	m/s	m³	µg	µg/m²/s		hrs	m/s	m³	µg		hrs	m/s	m³	µg	
	"Upwind" Position															
145-175	64.7	1.25	0.2287	4.46	24.4	-	64.2	1.20	0.2179	6.99	38.5	81.3	1.39	0.3196	1.38	6.0
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	3.44	16.2	30.5	1.44	0.1242	0.95	11.0
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	3.51	24.8	32.5	1.85	0.1700	3.97	43.2
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	3.23	28.5	49.8	1.39	0.1957	1.97	14.0
	"Before Trees" Position															
145-175	64.7	1.25	0.2287	9.60	52.5	23.3	64.2	1.20	0.2179	16.1	88.7	81.3	1.39	0.3196	20.61	89.6
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	15.5	72.9	30.5	1.44	0.1242	19.53	226.4
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	18.3	129.2	32.5	1.85	0.1700	11.44	124.5
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	14.8	130.5	49.8	1.39	0.1957	14.40	102.3
	"After Trees" Position															
145-175	64.7	1.25	0.2287	4.08	22.3	15.6	64.2	1.20	0.2179	3.84	21.2	81.3	1.39	0.3196	4.49	19.5
175-205	-	-	-	-	-	-	75.2	1.16	0.2467	4.03	19.0	30.5	1.44	0.1242	8.64	100.2
205-235	-	-	-	-	-	-	50.1	1.23	0.1743	8.66	61.1	32.5	1.85	0.1700	13.97	152.0
235-265	-	-	-	-	-	-	40.1	1.19	0.1349	8.80	77.6	49.8	1.39	0.1957	12.83	91.1

Comparison of "screened in" DPAS-MANDE data with automatic data, averaged 120º arc

During period 1 there were automatic monitoring data available at the "Before Trees" and "After Trees" positions for 4 adjoining sectors that had "screened-in" DPAS-MANDE data based on UKCEH winds. These were the sectors from 115º to 235º which formed a 120º arc that approximately covered the poultry activities associated with the 6000-bird shed. Tables 6.3.1.7 and 6.3.1.8 show these automatic data and the concurrent DPAS data. Table 6.3.11 compares the average concentrations from the DPAS-MANDE data and the automatic data during period 1, based on time-weighted averages evaluated across all 4 sectors i.e. based on the combined 120º arc from 115⁰ to 235⁰.

Table 6.3.11. Comparison of concentrations from DPAS and automatic monitoring at positions before and after trees during Period 1: time-weighted averages for 120º arc, based on UKCEH wind data

Position:	Concentration µg/m³	
	DPAS	Auto
Before Trees	73.4	70.4
After Trees	35.2	48.5

At the "Before Trees" position, the average DPAS and automatic concentrations across the 120º arc were 73.4 and 70.4 µg/m³ respectively, and so agreed within ~5%. At the "After Trees" position the DPAS and automatic concentrations were both reduced, to 35.2 and 48.5 µg/m³ respectively i.e. by 52% and 31% respectively. The greater reduction measured here by the DPAS may have been partly because its air inlet was 1.2m above ground, where winds were more likely to be intercepted and reduced by the treebelt. By contrast, the inlet to the automatic monitor was 1.8 m above ground, where winds were more likely to fly over the trees and so less likely to be intercepted and abated. The comparison in for the "Before Trees" position suggests that automatic monitoring and "screened-in" DPAS data agree within ~5% for averages over a few weeks and several 30º sectors.

DPAS-MANDE measurements of ammonia from neighbouring poultry farm

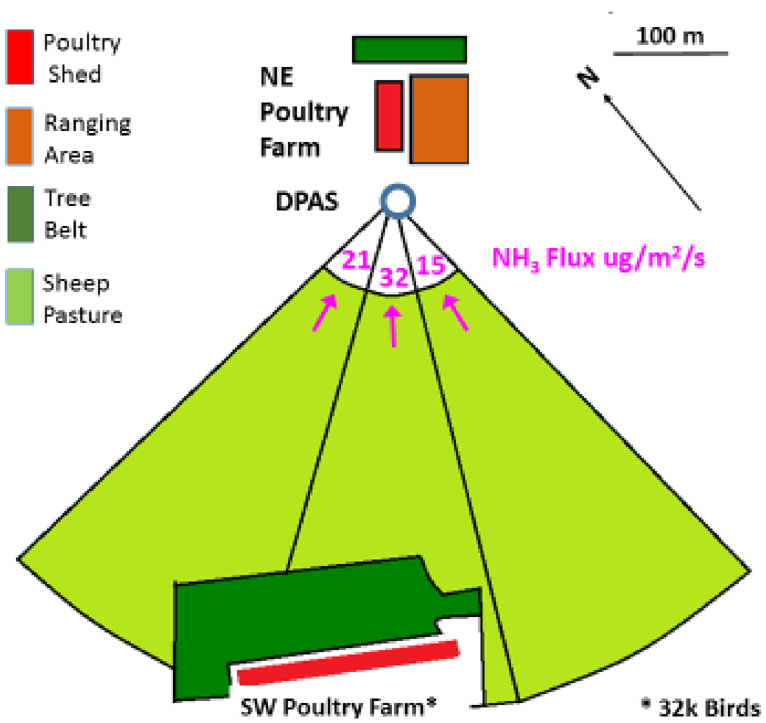


Figure 6.3.3 NH_3 fluxes at Upwind DPAS from neighbouring poultry farm (4-week sector averages)

Figure 6.3.1 shows there is a neighbouring poultry farm ~0.5km south-west of the intensive measurements farm. The neighbouring farm has a single shed that is ~200m long and about ~450m from the position of the "Upwind" DPAS (= DPAS 1) at the intensive measurements farm. Figure 6.3.3 shows that, when viewed from this DPAS position, the neighbouring farm shed covers an arc of ~25^o from ~210^o to ~235^o. Consequently most winds from the 30^o sector 205-235^o that are sampled at the "Upwind" DPAS come from angles covered by the neighbouring shed, and may therefore contain additional ammonia from that shed. By contrast, the adjacent 30^o sectors (175-205^o and 235-265^o) that are sampled at the "Upwind" DPAS only cover angles with sheep pasture, and may therefore only have background levels of ammonia with no extra ammonia from the neighbouring shed.

The fluxes measured by the "Upwind" DPAS for these three sectors were analysed in order to check if higher levels of ammonia came from the central sector that contained the neighbouring shed, compared to the adjacent sectors that contained only sheep pasture. "Screened-in" ammonia data were available at the "Upwind" DPAS for all 3 sectors during periods 3 and 4, based on NWP wind data. Table 6.3.12 compares the fluxes from these sectors for both periods combined i.e. for 4 weeks. The flux from the central sector that contained the neighbouring shed was more than the fluxes from each of the adjacent sectors that contained only sheep pasture, and 82% more than their average i.e. 32.0 v. 17.6 µg/m^2/s.

Table 6.3.12 also compares the concentrations from the same sectors for both periods combined. The concentration from the central sector that contained the neighbouring shed was more than the concentrations from the adjacent sectors, and 51% more than their average i.e. 21.4 v. 14.2 µg/m^3. The percentage excess of ammonia was lower for concentrations than for fluxes (51% v. 82%) because concentrations are sensitive to wind speeds, which were lower in the adjacent sectors than in the central sector. Specifically, the average wind speed in the adjacent sectors was 1.25 m/s compared with 1.47 m/s in the central sector.

Table 6.3.12. Comparison of ammonia at Upwind DPAS from "screened-in" sectors facing the neighbouring farm, based on periods 3+4 (combined) and NWP wind data

Sector		Flux	Conc.	Wind Speed
		µg/m^2/s	µg/m^3	m/s
Central (a)	*205-235^o*	32.0	21.4	1.47
Adjacent (b)	*175-205^o*	14.7	12.1	1.19
	235-265^o	20.5	16.3	1.30
	Average	17.6	14.2	1.25
Central/Average Adjacent		182%	151%	118%

(a) Central sector facing directly at the neighbouring farm.
(b) Adjacent sectors facing sheep pasture on either side of neighbouring farm.

Concentrations from sources that emit near ground level, like sheds and pasture, vary approximately inversely with wind speed. But fluxes from such sources are relatively unaffected by variations in wind speed, and therefore remain more directly proportional to emissions. Because fluxes depend less on wind speed, they are better than concentrations for the purpose of resolving emissions from near-ground-level sources, as demonstrated here where the DPAS samples are from sectors with different average wind speeds.

The 82% excess of flux from the central sector containing the neighbouring shed is consistent with that shed being a distinct source of ammonia in the district around the intensive measurements farm, and suggests that DPAS-MANDEs can detect and resolve poultry-shed ammonia over distances of ~0.5km. Figures 6.3.1 and 6.3.3 show there is a treebelt near the neighbouring farm, in the direction of upwind DPAS-MANDE. This implies that DPAS-MANDEs detected poultry-shed ammonia at ~0.5km even though it was partly abated by trees, and suggests they DPAS-MANDEs can be used to assess the longer-range effects of ammonia reduction by trees at a landscape scale.

6.3.10 Evaluation of ammonia reduction by trees

Transects, layouts and periods for evaluating ammonia reduction by trees

The "screened-in" DPAS data in Tables 6.3.7-10 were used to evaluate ammonia reduction by trees for sectors where winds crossed the treebelt. Reductions were evaluated for 5 directional transects as summarised in Table 6.3.13. Figures 6.3.5 and 6.3.6 shows the layouts of the first 4 transects i.e. the "Shed 30º sector", the "Shed 90º Quadrant", the "Ranging Area 30º/60º sector", and the "Overall 120º Arc". Figure 6.3.4 shows the layout of the 5th transect i.e. the "Background 30º sector".

Table 6.3.13. Transects and DPAS-MANDE sectors used to evaluate ammonia reduction by trees

Transect	Position			Comment
	Upwind *Bearing range*	Intermediate *Bearing range*	Downwind *Bearing range*	
Shed *30º Sector*	Before shed *205-235º*	Before trees *205-235º*	After trees *205-235º*	Covers 6000-bird shed and aligns with its long axis; substantially excludes Ranging Area.
Shed *90º Quadrant*	Before shed *175-265º*	Before trees *175-265º*	After trees *175-265º*	Covers 6000-bird shed and aligns with its long axis; includes adjacent part of Ranging Area.
Ranging Area *30º/60º Sector*	Before Shed *145-205º*	Before trees *145-205º*	After trees *175-205º*	Uses 2 sectors (30º and 60º) that substantially exclude the shed, and that substantially contain the Ranging Area and overlap over it.
Overall *120º Arc*	Before Shed *145-265º*	Before trees *145-265º*	After trees *145-265º*	Covers all Flock 15 poultry activities i.e. shed and all of Ranging Area.
Background *30º Sector*	Before Shed *115-145º*	n/a	After trees *115-145º*	Covers well-mixed "landscape" NH_3 from pasture; excludes poultry emissions. Trees cover only half of sector; other half is open (no trees).

Ammonia reductions were evaluated separately for concentrations and fluxes. Where possible, they were also evaluated separately for UKCEH and NWP wind data, in order to check if the results were sensitive to the type of wind data used. Reductions were evaluated over 4 or 6 weeks of poultry activities, based on combining 2 x 2-week periods. Because results were based on 4-6 weeks, rather than 2 weeks, they included more hours of airflow from each sector and so they were more likely to be representative e.g. of both daytime and night-time conditions.

Ammonia reductions by trees for 6-week periods

There were two transects where "screened-in" data were available for all 3 of periods 1, 3 and 4 i.e. for 6 weeks. Table 6.3.14 shows these situations, which used UKCEH wind data and comprised the Shed 30° sector and the Background 30° sector. For the Shed 30° sector, there was a 26% reduction in ammonia concentrations and fluxes between the "Before Trees" position (downwind of the poultry shed) and the "After Trees" position (downwind of the treebelt).

Table 6.3.14. Ammonia reductions by trees for transects with 6 weeks of monitoring

Transect	Source Of Wind Data	Duration		Wind speed .	Concentration µg/m³				Flux µg/m²/s			
		Periods	Time hours	m/s	Up-wind	Bef. Trees	Aft. Trees	% Redn.	Up-wind	Bef. Trees	Aft. Trees	% Redn.
Shed 30°	UKCEH	1+3+4	163.7	1.45	14.6	53.3	39.4	-26%	23.6	86.3	63.7	-26%
Backg. 30°	UKCEH	1+3+4	115.5	1.62	25.1	25.1	18.8	-25%	36.5	n/a (a)	27.3	-25%

(a) Not applicable as background air from 115-145° did not cross poultry activities before reaching trees.

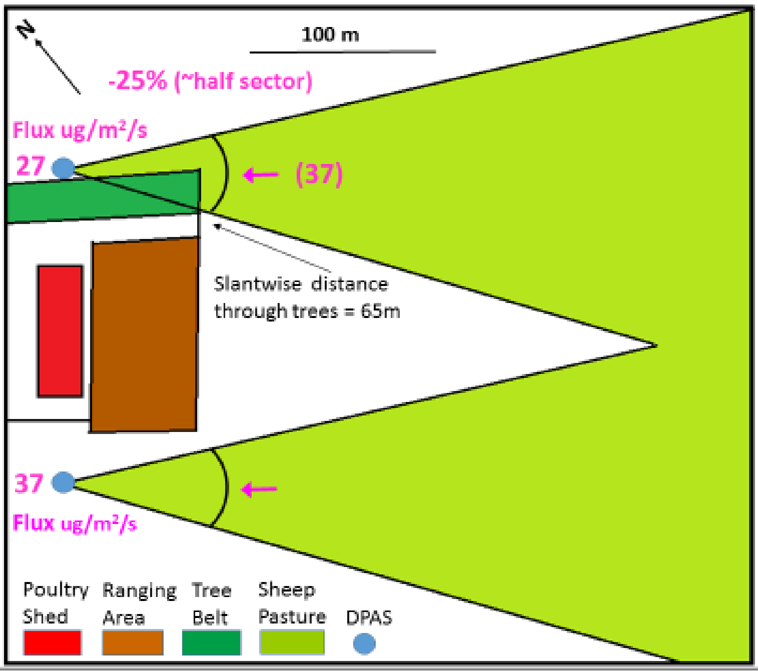


Figure 6.3.4 Background Ammonia fluxes (µg/m²/s) from pasture with and without partial interception and reduction by tree belt: 6-week-averages for DPAS-MANDE 30° sectors

The upwind air from the Background 30° sector contained ammonia from the neighbouring fields of sheep pasture. This airborne ammonia was likely to be well-mixed because the air came from the wider landscape, and not from poultry farms with localised ammonia plumes. It was therefore assumed that flux of background ammonia that approached the intensive measurements farm was homogeneous, and corresponded to the flux measured at the lower DPAS in Figure 6.3.4 i.e. 37 µg/m²/s. Based on the same assumption of homogeneity, the background ammonia flux that approached the upper DPAS, where it first reaches the tree belt, was estimated to be also 37 µg/m²/s. About half of this approaching sector of background air crossed obliquely through the tree belt on its way to the upper DPAS position. Specifically, it passed through about 65m of trees that reduced its ammonia content. However, the other half of this background air reached sector the upper DPAS position without passing through the tree belt i.e. without any potential for trees to reduce its ammonia. Table 6.3.14 shows that the concentrations and fluxes in the background sector air reduced by about 25% between (i) the approaching “Before Trees” situation (37 µg/m²/s) and (ii) the subsequent “After Trees” situation (27 µg/m2/s) where ~half of the air had passed through ~65m of trees. It is therefore estimated that if all of the background air had passed through -65m of trees, the reduction in ammonia would have been ~50%. It should be noted that this 50% reduction is solely due to interception by trees, and not due to any dispersion of a localised plume (because the approaching background air is homogenous and without localised plumes). The 50% reduction therefore represents ammonia interception by 65m of trees alone, without any reduction due to plume dispersion. This contrasts with the reductions obtained for the other transects which include some reductions due to dispersion of localised poultry plumes, as well as reductions by trees.

Ammonia reductions by trees for 4-week periods

Table 6.3.15 shows the percentage reductions in ammonia fluxes and concentrations by trees for 4-week periods at the first 4 transects, as summarised in Table 6.3.13. The percentage reductions in fluxes and concentrations were similar (within 1%), and they are also shown in Figures 6.3.5 for fluxes and Figure 6.3.6 for concentrations.

Table 6.3.15 Ammonia reductions by trees for transects with 4 weeks of monitoring

Transect	Source of Wind data	Duration		Wind Speed	Concentration µg/m³				Flux µg/m²/s			
		Per-iods	hours	m/s	Up-wind	Before Trees	After Trees	% Re-duced	Up-wind	Before Trees	After Trees	% Re-duced
Shed 30º	UKCEH	3 + 4	121.1	1.78	12.2	48.4	36.8	-24%	21.8	86.8	66.1	-24%
	NWP	3 + 4	82.6	1.47	21.7	86.4	65.7	-24%	32.0	127.3	96.9	-24%
Shed 90º	NWP	3 + 4	278.2	1.33	16.3	89.9	54.4	-39%	21.7	119.4	72.4	-39%
Ranging Area 30º	UKCEH	1 + 3	97.8	1.01	22.7	88.6	27.7	-70%	23.0	89.6	28.0	-69%
	NWP	3 + 4	105.7	1.24	11.8	94.4	34.2	-64%	14.7	117.2	42.4	-64%
Overall 120º	NWP	3 + 4	423.2	1.32	16.1	82.5	41.2	-50%	21.3	109.2	54.5	-50%

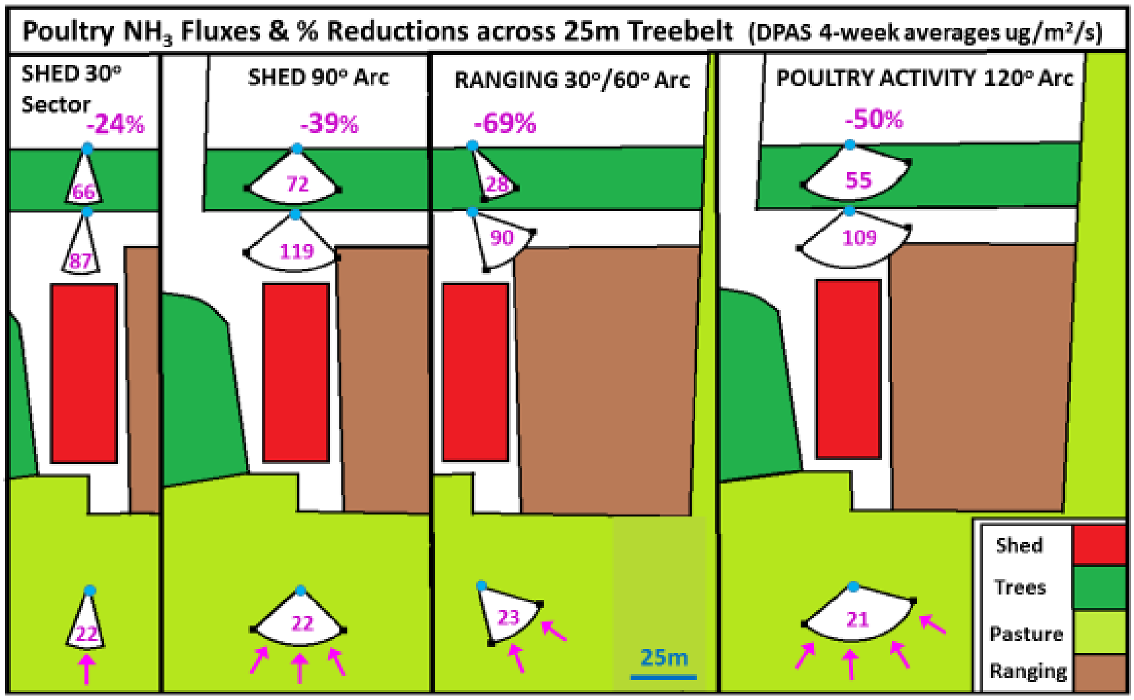


Figure 6.3.5 Poultry ammonia fluxes (µg/m²/s) and percentage reductions across 25m tree belt: 4-week-averages for individual/combined DPAS-MANDE 30° sectors

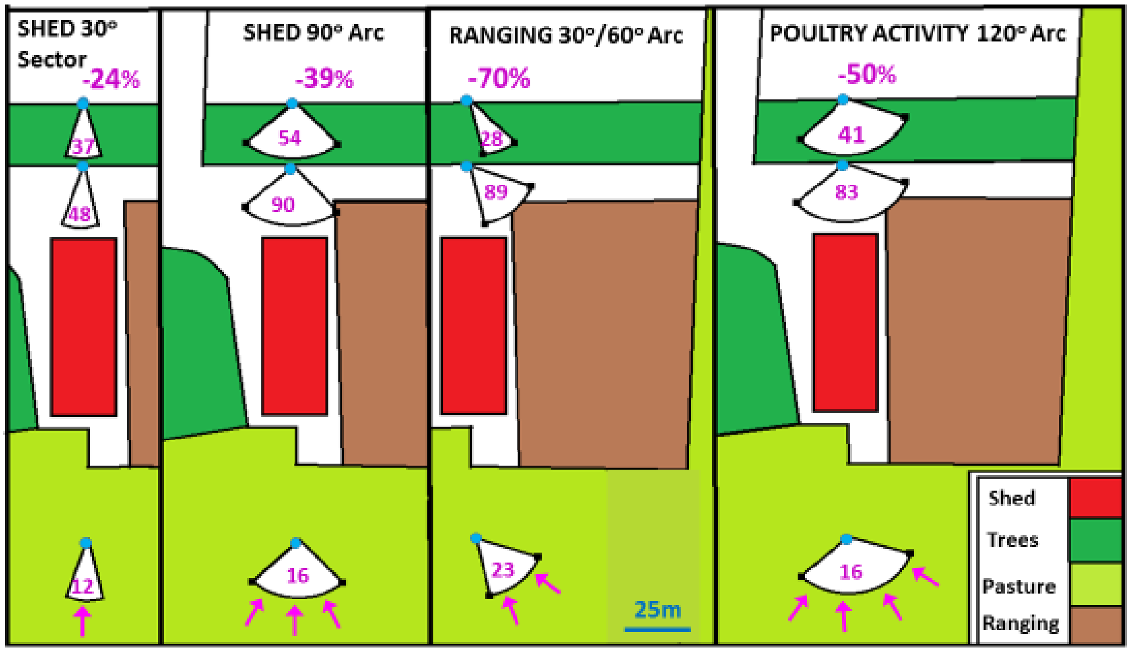


Figure 6.3.6 Poultry ammonia concentrations (µg/m³) and percentage reductions across 25m tree belt: 4-week-averages for individual/combined DPAS-MANDE 30° sectors

The results for the Shed 30° sector tend to confirm that ammonia fluxes and concentrations were reduced by ~25% for winds that blew along the length of shed and then crossed the treebelt. By contrast, the results for the Ranging Area 30° sector show that in this case the treebelt reduced ammonia concentrations and fluxes by ~70%. The greater percentage reduction for the Ranging Area, compared to the Shed, may be because its emissions were at ground level, and so were more likely to pass through the trees and be abated. By contrast, the emissions from the Shed were from its eaves at ~3m above ground, so they were more likely to pass over the trees and remain unabated. The results for the Shed 90^o quadrant show that when air from this direction had crossed the trees its ammonia was reduced by ~40%. This is consistent with the fact that the quadrant included emissions from both the Shed and the Ranging Area, for which the percentages reductions were ~25% and ~70% respectively. The results for the Overall 120^o Arc show that, when the wind was from this direction, the treebelt reduced the ammonia fluxes and concentrations from all poultry activities by ~50%.

Table 6.3.15 shows situations with 4 weeks of monitoring data where evaluated ammonia reductions can be compared for different wind data. For example, UKCEH and NWP wind data both show 24% reductions in ammonia concentrations and fluxes between the “Before Trees” and “After Trees” positions for the Shed 30^o sector. Also, UKCEH and NWP wind data both show reductions for the Ranging Area 30^o sector that are similar i.e. 69% and 64%, respectively. The similarity of the results obtained when using wind data from different sources suggests that modelled and measured data are both useful for evaluating DPAS samples. It follows that NWP data could be used to derive directional concentrations and fluxes from DPAS samples, instead of on-site meteorological measurement. This
would simplify future fieldwork, because there would be no need for meteorological instruments on or other powered monitoring equipment on site.

Ammonia reductions normalised to 25m of trees

The results presented for 4-week and 6-week periods in Tables 6.3.14-15 and Figures 6.3.4-6 involve different distances of airflow through the treebelt. For example, the distance for the “Shed 30^o sector” is ~25m because the airflow is at right angles to the 25m tree belt, but the distance for the “Ranging Area 30^o/60^o arc” is ~28m because the airflow is slightly oblique to the tree belt. Also, the distance travelled for the “Background 30^o sector” is ~65m because the airflow here is very oblique to the tree belt. The percentage reductions obtained for different distances of airflow through trees were normalised to a consistent distance of 25m, so that reductions could be compared on a like-for-like basis.

Table 6.3.16 shows the normalised amounts of percentage reductions in fluxes and concentrations for all 5 transects, as described in Table 6.3.16.. The lowest amounts of normalised reduction occur in the are 19% and -22% for the “Background 30o Sector” transect and are 19% and 22% for fluxes and concentrations, respectively. By contrast, the amounts of normalised reduction for the other transects are higher, and range from 24% for the “Shed 30o Sector” to 63% for the Tanging 30o/60o arc. This contrast is consistent with the fact that the reduction in the “Background 30o Sector” is solely due to ammonia interception by trees, with no contribution from plume dispersion, whereas the reductions in the other transects are supplemented by local plume dispersion, as discussed in Section 6.3.6.2.

Table 6.3.16 Reductions in fluxes & concentrations by trees (4 or 6-week averages):: summary for different transects showing emission height, distance through trees and reductions normalised to 25m

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 30^o 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.

6.3.11 Summary and discussion

Field trial basis

The Poultry 3 field trial was a first opportunity to deploy the DPAS-MANDE system alongside automatic ammonia monitors at an intensive agriculture site. The following points summarise and discuss the main results and findings from the work, but they are preliminary points from a first trial rather than definitive conclusions.

Sampling activities

The DPAS-MANDE system sampled airborne ammonia from 30º directional sectors over 2-week sampling periods. The samples were combined with meteorological data in order to evaluate directional concentrations and fluxes. The DPASs were relatively easy to deploy, because they are small and do not need power. 3 DPASs were placed in a line that ran from (i) a position "Upwind" of the intensive measurements farm poultry shed and ranging area, to (ii) a "Before Trees" position that was ~25m downwind of those poultry activities, and finally to (iii) an "After Trees" position that was a further 25m downwind i.e. after a 25m treebelt.

Backflows and data screening

When ammonia concentrations were first evaluated from DPAS samples, it was apparent that several samples had collected anomalously large amounts of ammonia e.g. compared to adjacent automatic monitoring data. The samples with excess ammonia were associated with periods and sectors that had low wind-speeds and short durations of airflow. It appeared that during these situations the wind was not strong enough to turn the DPAS so that its air inlet faced upwind. Consequently, "backflows" occurred that introduced excess ammonia into the open end of each MANDE i.e. into the end that should face downwind so it does not receive ammonia. Criteria were developed and applied to "screen-out" periods and sectors with "backflows", so that only periods and sectors with moderate-or-greater speeds and durations of wind were considered for further analysis - based on "screened-in" data.

Modification of DPAS design and materials

The DPASs used at Poultry 3 were designed to hold a range of different sampling media, and were therefore relatively heavy and thick (i.e. their depth from top to bottom had to be large enough to accommodate a range of different-sized sampling media). Their performance for ammonia monitoring with MANDEs could be improved by re-designing them explicitly for that purpose. For example, they could be: (i) fitted with baffles downwind of each MANDE to divert any backflows away from the open end of the MANDE that normally faces downwind, (ii) re-designed with a shallower depth that is just enough to hold MANDEs, (iii) remade with lighter materials, ceramic bearings, and a large vane - to maximise alignment with light winds. Further improvements could also be achieved by reducing the “slot” which guides air towards the 1mm orifice from 2mm to 1mm in depth, because this reduction would mean there was less potential for excess air to cause unwanted “cross-talk” flows between the DPAS channels.

Comparison of DPAS and automatic monitoring

DPAS data were “screened in” for 14 sectors, using measured wind data, and these data were used to evaluate DPAS concentrations for comparison with those from automatic monitoring. When evaluating DPAS concentrations, it was assumed that the airspeed that introduced ammonia into the MANDEs in each channel was the same as the external air speed. The average concentrations from the “screened-in” DPAS data and automatic data were 51.2 and 51.6 µg/m^3, respectively. A similar comparison was made for 9 sectors that were “screened-in” using wind data from Numerical Weather Prediction (NWP); in this case the average concentrations from DPAS and automatic data were 39.6 and 36.9 µg/m3 respectively. These comparisons tend to support the assumption that the internal airspeed is similar to the ambient wind speed.

Concentrations from “screened in” DPAS data were compared with automatic monitoring data during a 2-week period when both types of data were available at the “Before Trees” and “After Trees” positions. At the “Before Trees” position, the average DPAS concentration across four 30^o sectors was within 5% of the corresponding automatic value (the average concentrations were 73.4 and 70.4 µg/m^3 for DPAS and automatic values, respectively). At the “After Trees” position, the average concentrations from DPAS and automatic monitoring were both reduced, but the amount of reduction was more for the DPAS than for the automatic data i.e. 52% v. 31%. This may have been partly because the air inlet to the DPAS monitor was at a lower height than the inlet to the automatic monitor (1.2 v. 1.8 m), where trees may be more effective at reducing ammonia because ammonia would be less likely to pass over them.

Detection of ammonia from more distant poultry operations

In the same district as the intensive measurements farm, there is a neighbouring poultry farm shed to the south-west i.e. in the direction of the prevailing wind. The neighbouring shed is ~200m long, and lies ~500m from the 6000-bird shed that was the focus for intensive measurements, and ~450m from the “Upwind” DPAS near that shed. As seen from this “Upwind” DPAS, the neighbouring shed occupies most of one 30^o sector, but almost none of the two adjacent 30^o sectors - which faced extensive sheep pasture with only background levels of ammonia**.** The ammonia flux from the 30^o DPAS sector that faced the neighbouring shed was about 80% more than the average from the two adjacent 30^o sectors that did not face it. This distinct excess of ammonia from the direction of neighbouring suggested that DPAS-MANDE samplers can detect farm ammonia signals over longer distances than those considered at the intensive measurements farm i.e. over ~0.5km, compared to the ~50m. There was a treebelt near the neighbouring shed, that intervened between it and the “Upwind” DPAS, but that DPAS was still able to resolve the ammonia signal from the shed. This suggests that DPAS-MANDE samplers can detect residual ammonia signals, after reduction by treebelts, so that they could be useful for district-scale surveys of ammonia reduction by trees.

Reduction of background ammonia by trees

Ammonia concentrations and fluxes were monitored in well-mixed background air that approached one side of the intensive measurements farm from fields of sheep pasture. This monitoring was done at positions before and after the background air had passed obliquely through the treebelt. The results suggested that background concentrations and fluxes were reduced by about 50% due to passing through about 65m of trees. It is likely that this reduction occurred solely because the trees intercepted ammonia, and that it would not have been augmented by plume dispersion – because the well-mixed background air was not a plume source. By contrast, the ammonia concentrations and fluxes measured elsewhere around the intensive measurements farm did include dispersing plumes from poultry, so that the measured reductions in ammonia would have been due to plume dispersion as well as interception by trees.

Wind data from Numerical Weather Prediction

Ammonia concentrations and fluxes were evaluated separately for 2 sources of wind data i.e. on-site measurements by UKCEH, and Numerical Weather Prediction (NWP) data for the local area. The NWP data were at a nominal height of 10m above ground and had to be adjusted (decelerated) to the height of the UKCEH measurements at 2.3m. This adjustment harmonised overall wind speeds between the two sources of data, but it did not harmonise their amounts of time with winds in different sectors. The amounts of ammonia reduction by trees based on UKCEH and NWP data were comparable. This suggests that it may be feasible to evaluate DPAS samples using NWP data instead of having to make on-site wind measurements - which would simplify future fieldwork. But more studies are needed to adjust NWP data down from 10m without using measured data e.g. studies that use an evaporative de-purant in each DPAS channel to estimate the directional wind run without the need for wind measurements.

Reduction of poultry ammonia by trees

Changes in the concentrations and fluxes of ammonia in 30^o sectors were evaluated between "Before Trees" and "After Trees" positions, based on "screened-in" data for periods of 4-6 weeks. This involved combining 2 or 3 sampling periods of 2 weeks. It was concluded that:

- Ammonia concentrations and fluxes from a 30^o sector that mainly covered the shed were reduced by about 25% between the "Before Trees" and "After Trees" positions.
- Ammonia concentrations and fluxes from a combined 30^o/60^o arc that focussed on the ranging area and excluded the shed, reduced by about 65% between the "Before Trees" and "After Trees" positions.
- The greater reduction for the ranging area 30^o/60^o arc (65%), compared to the shed 30^o sector (25%), may have occurred because the ranging area emissions were at ground level, and so were more likely to be intercepted and abated by trees. By contrast, the shed emissions were from its eaves at ~3 m above ground, so that some of them may have passed over the trees and not been abated
- Ammonia concentrations and fluxes from a 90^o sector that covered the shed and part of the adjacent ranging area were reduced by about 40% between the "Before Trees" and "After Trees" positions. This intermediate percentage, between 25% and 65%, is consistent with the fact that the 90^o sector contains both the shed and the ranging area.

- Ammonia concentrations and fluxes from a 120^{o} sector that covered all Flock 15 poultry activities were reduced by about 50% between the “Before Trees” and the “After Trees” positions.

Normalised ammonia reductions

The distance that ammonia travelled through the treebelt varied between different DPAS-MANDE transects, because of differences in the angle between the belt and each transect. For example, airflows from the shed transect crossed the belt orthogonally through 25m of trees, whereas airflows from the background pasture crossed it obliquely through 65m of trees. In order to make like-for-like comparisons between different transects, the results of ammonia reduction measurements were normalised to a consistent distance of 25m The lowest normalised reductions occurred in background ammonia (-19% for fluxes; -22% for concentrations) which was consistent with these reductions being solely due to interception by trees, without any contribution from plume dispersion. The highest normalised reductions occurred from the ranging area (-69% for fluxes; -70% for concentrations), which was consistent with the ranging area emitting a ground-level plume that did not pass over the trees and dispersed downwind. The amounts of the 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.

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