Modelling agro-forestry scenarios for ammonia abatement in the landscape

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Abstract

Ammonia emissions from livestock production can have negative impacts on nearby protected sites and ecosystems that are sensitive to eutrophication and acidification. Trees are effective scavengers of both gaseous and particulate pollutants from the atmosphere making tree belts potentially effective landscape features to support strategies aiming to reduce ammonia impacts. This research used the MODDAS-THETIS a coupled turbulence and deposition turbulence model, to examine the relationships between tree canopy structure and ammonia capture for three source types—animal housing, slurry lagoon, and livestock under a tree canopy. By altering the canopy length, leaf area index, leaf area density, and height of the canopy in the model the capture efficiencies varied substantially. A maximum of 27% of the emitted ammonia was captured by tree canopy for the animal housing source, for the slurry lagoon the maximum was 19%, while the livestock under trees attained a maximum of 60% recapture. Using agro-forestry systems of differing tree structures near 'hot spots' of ammonia in the landscape could provide an effective abatement option for the livestock industry that complements existing source reduction measures.

Keywords: ammonia, agroforestry, nitrogen deposition

1. Introduction

Global ammonia emissions have increased substantially over the 20th and early 21st centuries, while future trends in ammonia emission will depend mostly on agricultural practices and the measures that are introduced to decrease ammonia emissions (van Vuuren et al 2011). The widespread use of the Haber–Bosch process since the 1950s has made it possible to produce ammonia and its derivatives in large quantities relatively inexpensively (Sutton et al 2008).

Together with increased emissions from fertilizer use, ammonia emissions from intensive livestock production systems have also increased as meat consumption per capita has increased across Europe, Asia and North America (Erisman et al 2007).

Excess nitrogen can cause eutrophication and acidification effects on semi-natural ecosystems, which in turn can lead to species composition changes and other deleterious effects (Bobbink et al 2010, Krupa 2003, Pitcairn et al 1998, Sheppard et al 2008, Van den Berg et al 2008, Wiedermann et al 2009). Species adapted to low nitrogen (N) availability are at a greater risk from this effect including many slow-growing lower plants, notably lichens and bryophytes. (Pearce and van der Wal 2002, Bobbink et al 1998). The quantification of risk associated with air pollution effects on ecosystems was defined by the United Nations Economic

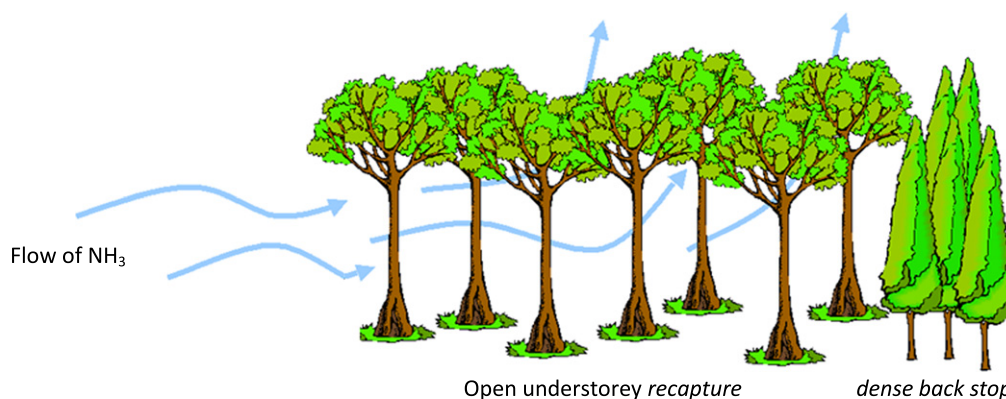[5] Author to whom any correspondence should be addressed.

Figure 1. Schematic diagram of a tree belt design to maximize recapture of ammonia. From Theobald *et al* (2003).

Commission for Europe (UNECE) (UNECE 1996) which describes the concept of 'critical loads' and 'critical levels': a critical load is the cumulated deposition under which an ecosystem/habitat is not affected by pollution while a critical level is defined as the effects above a certain threshold of concentration of a particular air pollutant. It is estimated that by 2020, 48% of sensitive habitats in the UK will still exceed the critical load for nutrient nitrogen (Hall *et al* 2006, Hallsworth *et al* 2010).

Legislative measures to reduce ammonia emissions in the UK and across Europe fall under several directives and protocols. As well as defining the concepts of 'critical loads' and critical levels', the UNECE multi-pollutant, multi-effect Protocol also set out a 2010 ceiling for emissions of sulphur, NOx, VOCs and ammonia. These were negotiated on the basis of scientific assessments of pollution effects and abatement options. The National Emission Ceilings Directive (NECD) (Council Directive 2001/81/EC) aimed to reduce emissions of pollutants that cause acidification, eutrophication and ground-level ozone in order to protect the environment and human health. These two frameworks have a long-term objective to ensure that pollutant levels remain below their critical loads and critical levels.

The EU Industrial Emissions Directive (2010/75/EU (IED)) regulates emissions from large, intensive pig (>2000 production pigs over 30 kg and 750 sows) and poultry units (>40 000 birds) through a system of permits. These 'hot spot' sources of ammonia emission can be readily deposited to nearby sensitive ecosystems and protected sites (Loubet *et al* 2009). Designated sites like Special Areas of Conservation (SAC) and Special Protected Areas (SPA) are managed under the Habitats Directive (92/43/EEC on the Conservation of natural habitats and of wild fauna and flora) and the Birds Directive (79/409/EEC). Both directives provide a high level of protection to the Natura 2000 network by taking a precautionary approach to controlling polluting activities. Agricultural industries (i.e. farmers) have to report their emissions and show that they are not posing a likely significant threat to the integrity of the protected site.

Because of their effect on turbulence, trees can be effective scavengers of both gaseous and particulate pollutants from the atmosphere (Beckett *et al* 2000, Nowak 2000)

with dry deposition rates to forest exceeding those to grassland by typically a factor of 3–20 (Gallagher *et al* 2002, Fowler *et al* 2004). This implies that the conversion of grassland and arable land to trees or targeted management of existing wooded areas, can be used to promote the removal of ammonia from the atmosphere, thereby reducing the potential impacts on nearby sensitive ecosystems and to some extent long-range transport of these pollutants. In a modelling study, Dragosits *et al* (2006) showed that tree belts can reduce deposition to sensitive ecosystems, with trees surrounding the sensitive habitats being more effective than trees around the sources for their scenarios. The capture of ammonia by surrounding vegetation has been studied by Patterson *et al* (2008), who observed lower NH_3 concentrations were measured when potted trees were present downwind of the poultry house fans compared with when the trees were removed (16.4 versus 19.3 ppm). Modelling research undertaken by Asman (2008) on the entrapment of ammonia by shelterbelts showed that capture of dry deposited gaseous ammonia increased with the height of the shelterbelt and the stability of the atmosphere (favouring neutral conditions), but decreased further away from the source to the shelterbelt. At 200 m away from a source the model predicted that a maximum 37% of the emission of a ground level point source of ammonia can be dry deposited before the plume reaches a shelterbelt that is located 200 m downwind. Then another 11% can be removed by a 10 m high shelterbelt.

Experimental approaches to measure ammonia recapture carried out by Theobald *et al* 2001, recorded a 3% recapture from throughfall measurements. While previous modelling of the MODDAS model (Theobald *et al* 2003) showed a recapture of ammonia emissions up to 15%. In this study we evaluated different tree planting designs near ammonia sources using the MODDAS-THETIS model to quantify optimal designs to capture ammonia thereby protecting nearby vulnerable ecosystems. The MODDAS-THETIS 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 examine how tree configuration and structure can be optimized to maximize NH_3 capture. Potential ammonia recapture
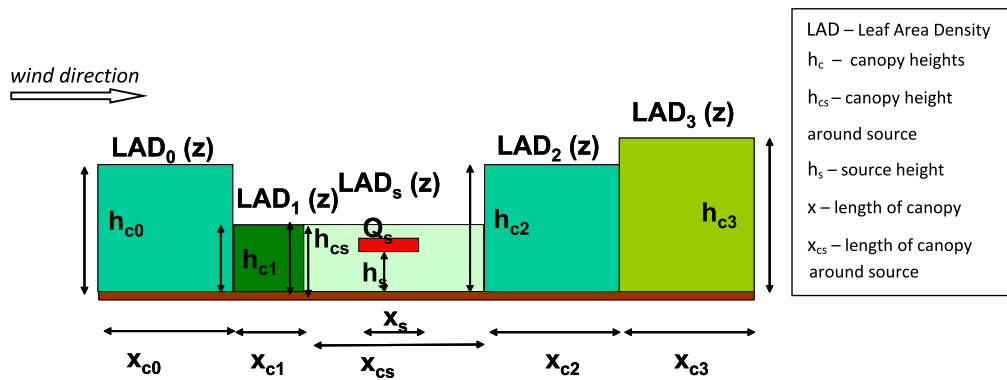
Figure 2. General model scheme of the woodland and source geometry that was tested in the scenarios. The shaded green boxes reflect different lengths (x_c) and heights (h_c), and LADs of canopy blocks. There is no limit to the different canopy structures that can be added to the model. The red box represents the source (Q_s) with a specified height (h_s) and downwind length (x_s). Indexes 0 to 3 to LAD, x_c and h_c correspond to canopy number, while index s corresponds to the source location.

is assessed and interpreted in terms of practical farm management approaches.

2. Methodology

There are two important considerations (figure 1) when designing tree systems for ammonia recapture:

(1) To get the ammonia into the woodland and through the densest part of the canopy, a reasonably open understorey would be necessary to prevent the ammonia passing over the top of the woodland and acting as a block to the airflow.

(2) Prevention of the loss of ammonia out of the downwind edge of the woodland. To stop this happening, a region of dense vegetation could be planted at the downwind edge to act as a backstop and force the ammonia up through the canopy as shown in figure 1.

MODDAS-THETIS is a flexible two-dimensional (along wind and vertical) model that can be used to examine the ammonia abatement potential of agro-forestry 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). THETIS is an Eulerian (k-ε) turbulence model designed for transfer within the planetary boundary layer as well as within a plant canopy (Foudhil *et al* 2005). The two models are coupled together such that the output of the THETIS model serves as the turbulence input of the MODDAS model, namely the horizontal (u,v) and vertical (w) components of the wind velocity, and the dissipation rate of the turbulent kinetic energy (ε). Both models have been validated in conditions similar to those modelled here, specifically MODDAS in an ammonia release experiment over a developed maize canopy and a grassland (Loubet *et al* 2006), and THETIS over several canopy arrangements (Foudhil *et al* 2005, Dupont and Brunet 2006). The coupling of the two models requires the partitioning of the turbulent kinetic

energy (k) into its three components (σu, σv and σw). By considering the equality of Eulerian and Lagrangian turbulent diffusivities (Raupach 1989) and by empirically setting the horizontal partitioning (based on Loubet 2000):

$$\alpha_{uv} = \sigma_u/\sigma_v = 1.25. \tag{1}$$

Then the vertical partitioning is calculated as:

$$\alpha_w = \sigma_w/(\sigma_u + \sigma_v + \sigma_w) = 0.37. \tag{2}$$

The model scenario setup is based around a woodland schema as shown in figure 2, where different blocks of woodland or canopy (c) are formed by varying the height of canopy (h_c), the length of canopy (x_c), the leaf area density profile (LAD(z)), the LAI (not shown in the figure), the source strength (Q_s) and the source length (X_s). 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 maximize ammonia recapture in the model run.

The vertical canopy structure of trees can be represented by the LAD which is the surface of leaves per unit volume. LAIs, the surface of leaves per unit ground surface area, are used to normalize the relative LAD profiles to produce LAD as a function of height. LAI values typically range from 0 for bare ground to $\geqslant 6$ for a dense forest. Five characteristic canopy profiles are illustrated in figure 3. LAD-0 is a flat canopy block profile from crown to base, LAD-1 is a canopy denser at the top and brashed toward the bottom, LAD-2 is a canopy with a marked crown, LAD-4 is like LAD-2 but with an additional bottom shrub layer near the ground, and LAD-10 is a coniferous profile with brashed bottom.

2.1. Source types

Three source types were tested representing three livestock production systems: poultry housing, a waste storage system (slurry lagoon with crust) and free-range poultry under tree cover. For each source type, the MODDAS-THETIS model was used to examine the recapture efficiency of tree planting around these sources looking at different canopy structure
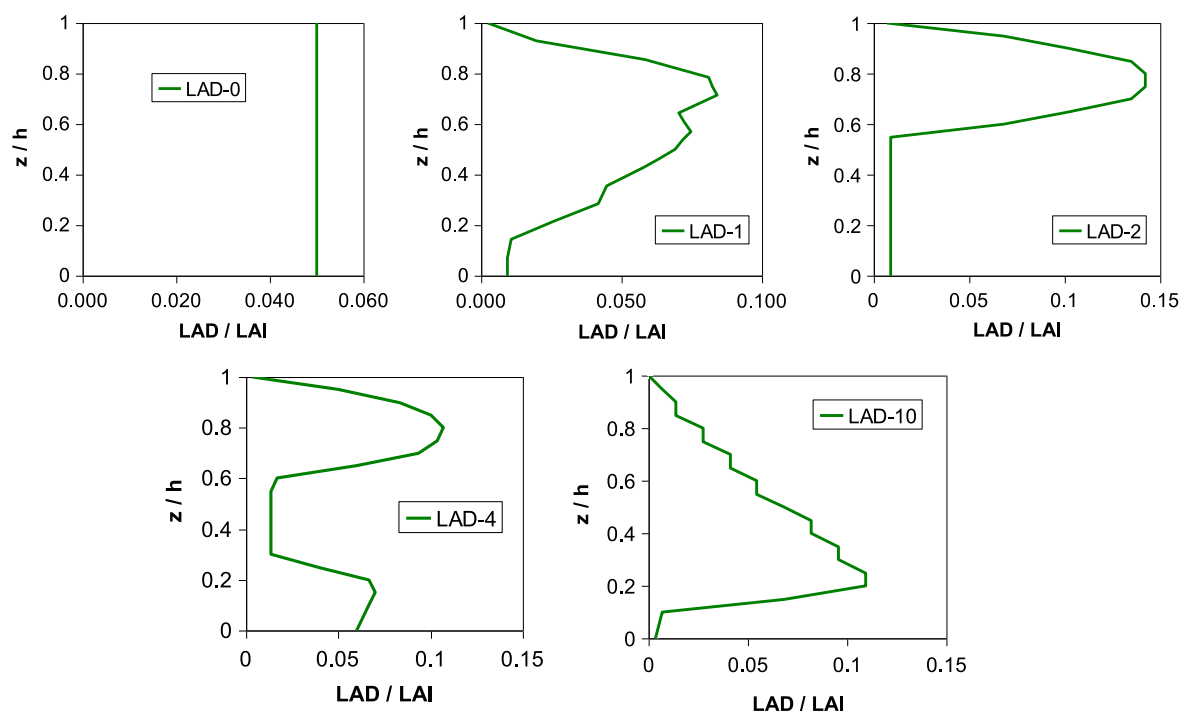
Figure 3. Leaf area density (LAD(*z*)) profiles of the canopies (og height *h*) used in the MODDAS-THETIS simulations. LAD(*z*) are a function of height showing the vertical canopy structure from the crown to the ground. All canopy profiles were used in these scenarios.

scenarios, lengths and differing LADs and LAIs to obtain an estimate of recapture potential.

For these three source types, the 'main canopy' was defined as the open understorey surrounding or above the source, while an optional dense 'backstop' canopy was also included. The backstop serves to capture NH_3 as it leaves the main canopy.

The source types, visualized in figure 4, were:

(1) a housing source of ammonia that was emitting at a height of 2–2.5 m height, with an along wind length of 4–5 m and with a source strength of 300 kg NH_3-N yr^{-1} (figure 3). Up to 39% of the UK's ammonia emissions comes from housing systems where hard surfaces prevent urine and manure being absorbed easily (compared with contact with the soil) (Misselbrook *et al* 2010).

(2) a slurry lagoon which was considered to emit at a height of 0.1–0.2 m, with a source strength of ~400 kg NH_3-N yr^{-1} (figure 4). Up to 6% of UK emissions of ammonia are estimated to come from slurry storage systems (Misselbrook *et al* 2010). Emission depends more on the surface area of slurry/manure in contact with the air rather than the total amount of slurry/manure stored.

(3) an 'under-storey' source, in which the emissions (e.g. from free-range chickens) were at a height of 0.1–2 m under the canopy, with a source strength of 625 kg NH_3-N yr^{-1} (figure 5). In 1946 nearly 98% of the UK flock of poultry layers were free-range. By 1980 95% were in cage systems (FAWC 1998). Out of the 26 million poultry egg-layers in the UK, free-range layers

currently account for around 38%. However, although these birds have access to the outdoors they spend a significant part of their time within the barn itself (Dawkins *et al* 2003).

It should be noted that since the ammonia concentration is linearly related to the source in the model (see Loubet *et al* 2006), one can compare the three situations by normalizing the concentration or the deposition by the source strength. A set of runs (on the housing source type only) were set up to examine the effect of changing the source strength by a factor of 100.

2.2. Scenarios

For each of the three source types, scenarios were set up by altering LAD, LAI, canopy height, source strength, and canopy length (table 1). These scenarios were run with neutral atmospheric stability, and the wind speed at 50 m upwind of the source was set to 5 m s^{-1}. For each scenario, symmetrical and non-symmetrical (i.e. only downwind) canopy structures were assessed.

2.3. Model parameterization

The deposition parameters were selected to reproduce realistic deposition rates. The stomatal resistance was modelled with a Jarvis approach (equation 3)

$$R_s = R_{smin}\left(1 + \beta_s/PAR\right),\qquad(3)$$

where PAR is the photosynthetically active radiation (W m^{-2}), R_{smin} (=60 s m^{-1}) is the minimum stomatal resistance and β_s (=7) is the stomatal response to light. The

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Table 1. Model scenarios for the three source types—housing, lagoon, and understorey livestock. The green boxes shaded show the differing sets of changing parameters that are being compared. The backstop canopy was set with a LAD 10 (coniferous tree profile). Symmetrical means that the canopy profiles are identical in the upwind and downwind direction.

Model scenario	Design	Main canopy length	LAI	Height (m)	LAD profile	Back-stop length (m)	LAI	Canopy height (m)
Housing 1	Symmetrical	30	6	10	0	0	—	—
Housing 2	Downwind	30	6	10	0	0	—	—
Housing 3	Downwind	25	3	10	1	5	6	10
Housing 4	Downwind	25	3	10	4	5	6	10
Housing 5	Downwind	25	3	10	10	5	6	10
Housing 6	Downwind	25	3	10	2	25	6	10
Housing 7	Downwind	25	3	10	2	50	6	10
Housing 8	Downwind	25	3	10	10	50	6	10
Housing 9	Downwind	50	3	10	10	50	6	10
Housing 10	Downwind	100	3	30	10	50	6	30
Housing 11 Source * 10	Symmetrical	30	6	10	0	0	—	—
Housing 12 Source * 1	Symmetrical	30	6	10	0	0	—	—
Housing 13 Source/10	Symmetrical	30	6	10	0	0	—	—
Lagoon 1	Symmetrical	30	6	10	0	0	—	—
Lagoon 2	Downwind	30	6	10	0	0	—	—
Lagoon 3	Downwind	25	3	10	0	5	6	10
Lagoon 4	Downwind	25	1	10	0	5	6	10
Lagoon 5	Downwind	25	3	10	2	5	6	10
Lagoon 6	Downwind	25	3	10	4	5	6	10
Lagoon 7	Downwind	25	3	10	10	5	6	10
Lagoon 8	Downwind	25	3	10	2	25	6	10
Lagoon 9	Downwind	25	3	10	2	50	6	10
Understorey 1	Symmetrical	100	3	10	0	0	—	—
Understorey 2	Symmetrical	100	3	10	0	5	6	10
Understorey 3	Symmetrical	100	3	10	0	10	6	10
Understorey 4	Symmetrical	100	3	10	0	25	6	10
Understorey 5	Symmetrical	100	3	10	0	50	6	10
Understorey 6	Symmetrical	100	6	10	0	50	6	10
Understorey 7	Symmetrical	100	6	10	1	50	6	10
Understorey 8	Symmetrical	100	6	10	2	50	6	10

cuticular resistance was set with equation 4

$$R_{\mathrm{w}} = R_{\mathrm{wmin}} e^{([1-\mathrm{RH}]/b\mathrm{w})}, \qquad (4)$$

where $R_{\mathrm{wmin}} = 7$ s m^{-1} is the minimum cuticular resistance and $\beta w = 7$ is the response to relative humidity RH (Massad *et al* 2010). The PAR above the canopy was set to 400 W m^{-2} and RH is the relative humidity in the canopy (set to 90% in order to study conditions favourable to NH$_3$ deposition). The ammonia emission potential of the canopy and soil was set to zero ($\Gamma = 0$). It should be noted that under real-life conditions there is a potential for saturation of the surfaces that are exposed to high loads of ammonia and therefore it should be stressed that the estimated deposition is an upper limit, with small cuticular and stomatal resistances and a zero compensation point in order to assess the effects of canopy structure.

2.4. Sensitivity analysis

To take into account the yearly variations of abiotic factors like temperature, relative humidity and radiation we have

done a run for each calendar month simulating variations in key parameters. We have also looked at the effect of loss of leaves in deciduous trees during winter months by varying the LAI of the main canopy for each month. The runs were based on the Housing 7 scenario (table 3).

3. Results

A detailed array of configuration scenarios was run for each of the three source types, the results from which are summarized in tables 3–5. The key results are how much ammonia was deposited (as % of emitted NH$_3$) and in which part of the woodland schema the deposition occurred.

3.1. Housing scenarios

In the Housing scenarios (table 2), the maximum NH$_3$ deposition simulated was 27% in Housing 9 which had a 50 m downwind canopy (LAI = 3 m^2 m^{-2}, LAD profile = 10), 50 m
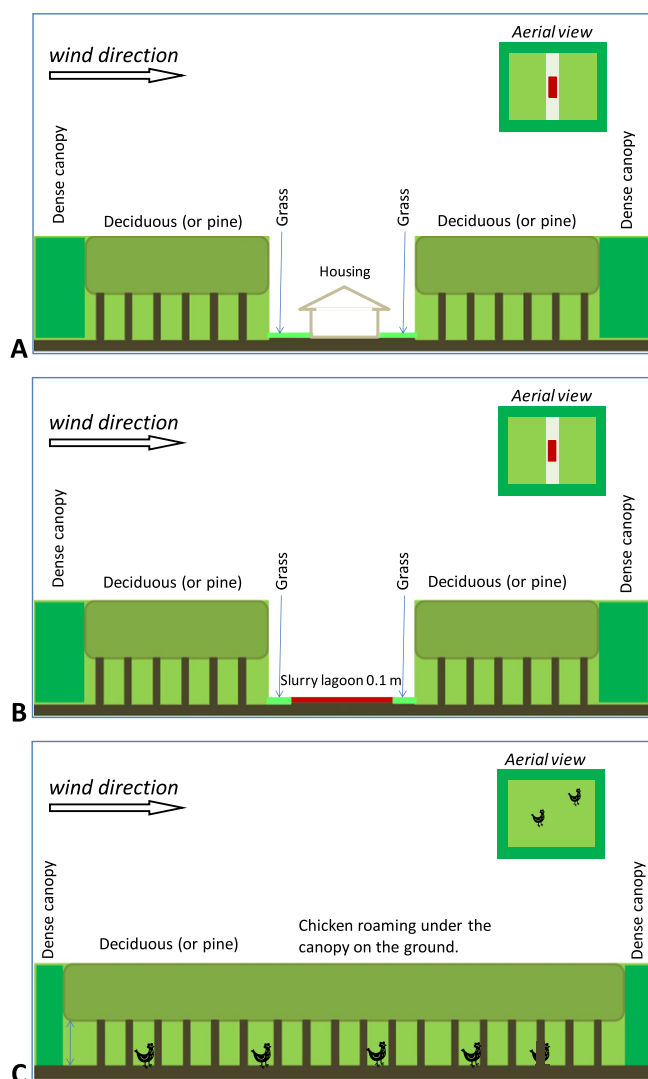
Figure 4. Visualization of example source types for tree belts upwind and downwind: (A) Housing source type. (B) Lagoon source type (red line), a variant of the housing scenario and (C) under-storey source scenario with free-ranging chickens. The 2D aerial view (top right) shows the scheme from above.

backstop (LAI = 6, LAD = 10,). The deposition in the other scenarios ranged between 7% and 25% of the emission.

Comparing Housing 1 and Housing 2, where the only difference is the presence of the symmetrical canopies, the total deposition does not differ much, with the symmetrical situation giving slightly estimated smaller deposition rates even though part of the deposition occurs in the upwind canopy due to backward diffusion. With housing runs Housing 3, 4 and 5 the effect of varying the LAD in the main canopy is observed (see figure 3 for corresponding LAD profiles). NH_3 deposition increased with LAD profiles 1, 4 and 10, with the LAD-10 profile (coniferous profile with 15–20% of the bottom free of leaves) recapturing the most NH_3. The deposition increases with the following order of LAD: LAD-1, LAD-2, LAD-4, LAD-0, LAD-10. Housing 6 and Housing 7 demonstrate that having a longer backstop increases deposition (from 16% to 25% in these cases). Most

of the modelled deposition in these scenarios occurs in the backstop and the proportion deposited in the main canopy remains stable with LAD-2 but decreases with LAD-10 (when the length of the backstop increases). The deposition in the backstop is not proportional to the length of the backstop.

Increasing the main canopy length, when the backstop length is set to 50 m (HS 8 & 9), increases the proportion of NH_3 recaptured significantly in the main canopy, but at the same time decreases the deposition in the backstop. The two effects counteract each other resulting in a net increase of only 3% in recapture efficiency. Another comparison can be made between Housing 7 and 8 which compares LAD 2 (brashed trunk) with LAD 10 (coniferous profile). In both cases the deposition is estimated at 25% of the emission although the backstop plays a larger role in LAD 2 (20%) compared with LAD 10 (16%).

The increase of the canopy height from 10 to 30 m with a constant LAI leads to a decrease in the deposition rates (Housing 9 and Housing 10). This is primarily due to a decrease in LAD, hence leading to a higher wind speed within the canopy and an increase in the turbulent mixing at the source location (asymmetrical scenario).

Housing runs 11 to 13 show the effect of changing the source strength by up to 100%. The difference is small in the deposition when the source is multiplied by 100 with the likely differences being due to cumulated rounding errors. We can however conclude that the model is indeed linear, i.e. the concentration and deposition are both proportional to the source strength.

3.2. Lagoon scenarios

In the lagoon scenarios (table 3), the percentage recapture is in general smaller than in the housing scenarios. The same effects can be seen, except that the LAD profile has an inverse effect on the deposition in Lagoon 3, and in runs Lagoon 5–7 the maximum deposition is obtained with the constant LAD profile (LAD-0). The concentration profile pattern has a maximum remaining very close to the ground when compared to the housing scenarios. In the lagoon scenarios, the source is at the ground where the wind speed tends to zero and hence mixing is slow, while in the housing sceanrios, the source is higher where mixing is more efficient. Hence the main differences are linked with the LAD profile characteristics near the ground. When open canopies with structures near the base (e.g. LAD-2) are used (Lagoon 8 and 9) then a long backstop is required to achieve comparable deposition rates to those with LAD-0.

3.3. The understorey scenarios

In the understorey scenarios (table 4), the capture increased from 15% to 37% for a backstop canopy length increasing from 0 to 50 m respectively (scenarios 1–5, LAI main canopy = 3, LAD main canopy=0). The percentage captured in the main canopy increased linearly with the canopy LAI (runs Understorey 4–5), but a canopy LAD denser at the top of the canopy (LAD-1), was less efficient in capturing NH_3
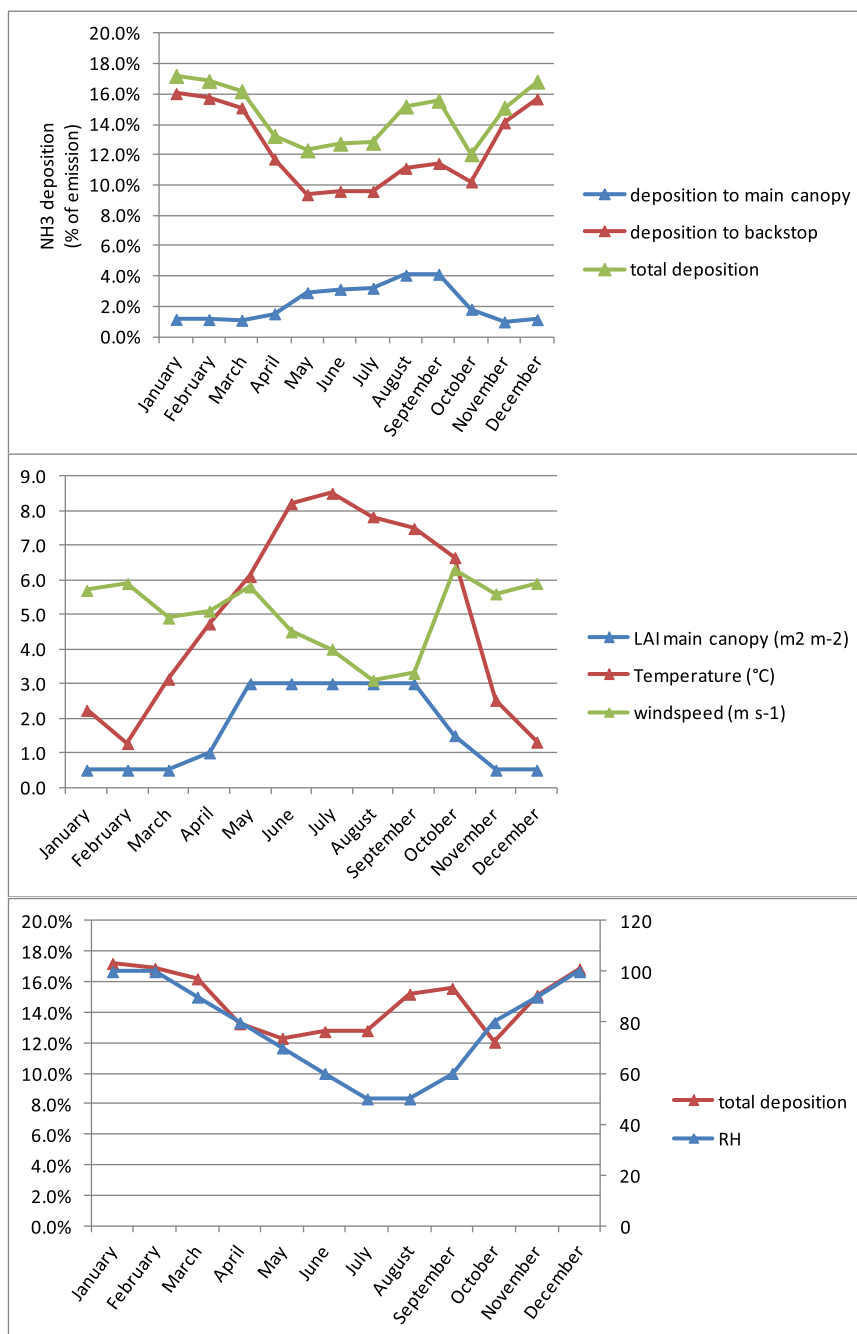
Figure 5. Graphs from table 6 showing the monthly fluctuations in abiotic factors and deposition captured in the canopy.

than a homogeneous LAD (runs Understorey 6–8). It is noted that Understorey 6 had the largest recapture percentage of all the scenarios considered.

3.4. Sensitivity analysis

The sensitivity analysis shows the change in deposition in the canopy over the year with higher capture in the summer months as the main canopy is more effective at capturing ammonia (table 6). However, when a varying RH is applied (table 7) the opposite is true as the winter months capture more deposition mainly due to the effect of the back-stop alone. RH over the summer has a significant negative effect on both main and back stop canopies.

Figure 5 shows the monthly changes in LAI, wind speed, temperature and RH, as well the changing deposition captured by the canopy throughout the year. The reduction in RH is compensated by the reduction in wind speed in June to September which explains why the deposition is maintained high during this period (bottom graph).

3.5. Concentration fields

For the symmetrical scheme (Housing 1), the presence of canopy both upwind and downwind of the source increases

the vertical dispersion and also the upwind dispersion due to the increased turbulent kinetic energy (figure 6, Housing 1). The asymmetrical scheme, Housing 2, shows a downstream decrease in the NH$_3$ concentration inside the canopy, but there is a subsequent increase in downwind concentration from the canopy due to a (calm air) recirculation zone. The scheme with a longer main canopy and longer backstop (Housing 9) leads to a decrease in the concentration in the canopy which is similar to the concentration field simulated with a smaller main canopy (Housing 1). In the case of the lagoon, the same behaviour is observed for the NH$_3$ concentration with or without an upwind main canopy (data not shown).

In the understorey scenarios model runs, the ammonia concentration can vary significantly depending on the canopy density (LAD and LAI). Indeed, with a quite open canopy (Understorey 5, LAI = 3), the maximum concentration reaches a level similar to the maximum concentration in the housing case, but when the canopy is very dense (Understorey 6, LAI = 6), the concentration is much larger and reaches more than 4000 μg NH$_3$ m^{-3} (figure 7). This can be explained by the very small level of turbulence and low wind speed in the canopy in the dense scenario, hence leading to the accumulation of high NH$_3$ concentrations.

3.6. Deposition patterns

The NH$_3$ deposition patterns in the housing scenarios follow the concentration patterns but are also affected by the LAD patterns (figure 3). Figure 8 illustrates the difference of having no back-stop (top panel) compared with a 50 m back-stop (lower panel). Interestingly, deposition to main canopy structures with lower LAIs (LAI = 3) is estimated to have higher deposition rates (15%) than denser back-stop canopies (LAI = 6) of a similar length (12%) as the main canopy is sufficiently long to capture most of the ammonia (Housing 9). This is also due to the concentration being much larger near the source than in the backstop.

The deposition pattern in the understorey scenarios varied a lot depending on the concentration levels, and the LAI

and LAD patterns. Figure 9 illustrates this when comparing a situation with a quite open canopy (LAI = 3 Understorey 5), with a situation with a dense main canopy (LAI = 6, scenario 6). The deposition is only significant in the backstop for the less dense canopy (37% recapture—Understorey 5) while it is very large throughout the main canopy and the backstop in the dense canopy scheme (60% recapture—Understorey 6).

3.7. Discussion and conclusions

This study has investigated housing, storage lagoon and understorey emission sources of ammonia and the use of trees to mitigate emissions by planting upwind and downwind of the source.

The modelling results estimate that maximum deposition rates of 27% for housing sources and, 19% for slurry lagoon sources can be attained, while 60% deposition for understorey systems is possible (although it is noted that the dense canopy would not be suitable for free-ranging chickens). The comparison between housing systems with woodland surrounding the housing unit (symmetrical) and woodland downwind of the source only (asymmetrical) shows that there is little additional deposition upwind of the source, but local meteorological conditions (e.g. wind direction) should be assessed before only planting on one side of a source. However, it may be desirable, due to the need to reduce costs, to plant on the downwind side of a source for predominant wind directions. It would be desirable to plant any woodland structure around a housing source as reduced deposition to semi-natural areas can help to protect sensitive species and habitats from nitrogen deposition effects.

LAI and LAD together with canopy length have the most effect on deposition rates within the range of scenarios tested here. The deposition rate increased roughly in proportion to the LAI, when the LAI and the LAD are identical in the main and the backstop canopies. Optimal designs included backstop structures of high LAI (dense canopy structures) which have the ability to prevent ammonia escaping underneath the canopy and out the sides and back of the canopy. Dense backstop structures were also found to lower the wind

Table 2. Monthly variation scenarios showing changes in LAI (main canopy) to mimic leaf loss over winter, photosynthetically active radiation (PAR), temperature (*T*a), relative humidity (RH), and wind speed.

Monthly variation in the deposition	LAI Main canopy m^2 m^{-2}	LAI Backstop m^2 m^{-2}	PAR W m^{-2}	Ta °C	RH %	Wind speed m s^{-1}
January	0.5	6.0	134	2.2	100	5.7
February	0.5	6.0	201	1.3	100	5.9
March	0.5	6.0	340	3.1	90	4.9
April	1.0	6.0	516	4.7	80	5.1
May	3.0	6.0	668	6.1	70	5.8
June	3.0	6.0	790	8.2	60	4.5
July	3.0	6.0	628	8.5	50	4.0
August	3.0	6.0	616	7.8	50	3.1
September	3.0	6.0	418	7.5	60	3.3
October	1.5	6.0	271	6.7	80	6.3
November	0.5	6.0	132	2.5	90	5.6
December	0.5	6.0	87	1.3	100	5.9

Table 3. Model scenarios and results for the housing source. The green shaded boxes show the sets of varied parameters that are being compared.

Model scenario	Design	Main canopy length	LAI	Height (m)	LAD Profile	Back-stop length (m)	LAI	Canopy height (m)	% TOTAL deposited	% Deposited upwind of the main canopy (x_{c0})	% Deposited in main canopy (x_{c1})	% Deposited in back-stop (x_{c2})
Housing 1	Symmetrical	30	6	10	0	0	—	—	16%	2%	14%	0%
Housing 2	Downwind	30	6	10	0	0	—	—	17%	0%	17%	0%
Housing 3	Downwind	25	3	10	1	5	6	10	7%	0%	6%	1%
Housing 4	Downwind	25	3	10	4	5	6	10	9%	0%	7%	2%
Housing 5	Downwind	25	3	10	10	5	6	10	12%	0%	10%	2%
Housing 6	Downwind	25	3	10	2	25	6	10	16%	0%	5%	11%
Housing 7	Downwind	25	3	10	2	50	6	10	25%	0%	5%	20%
Housing 8	Downwind	25	3	10	10	50	6	10	25%	0%	9%	16%
Housing 9	Downwind	50	3	10	10	50	6	10	27%	0%	15%	12%
Housing 10	Downwind	100	3	30	10	50	6	30	17%	0%	12%	5%
Housing 11 Source *10	Symmetrical	30	6	10	0	0	—	—	16.1%	—	—	—
Housing 12 Source * 1	Symmetrical	30	6	10	0	0	—	—	16.5%	—	—	—
Housing 13 Source/10	Symmetrical	30	6	10	0	0	—	—	17.4%	—	—	—

Table 4. Model scenarios and results for the 'slurry lagoon' source. The green shaded boxes show the sets of varied parameters that are being compared.

Model scenario	Design	Main canopy length (m)	LAI	Height(m)	LAD Profile	Back-stop length (m)	LAI	Canopy height (m)	% Total deposited	% Deposited upwind of the main canopy (x_{c0})	% Deposited in main canopy (x_{c1})	% Deposited in back-stop (x_{c2})
Lagoon 1	Symmetrical	30	6	10	0	0	—	—	19%	2%	17%	0%
Lagoon 2	Downwind	30	6	10	0	0	—	—	19%	0%	19%	0%
Lagoon 3	Downwind	25	3	10	0	5	6	10	11%	0%	9%	2%
Lagoon 4	Downwind	25	1	10	0	5	6	10	5%	1%	2%	2%
Lagoon 5	Downwind	25	3	10	2	5	6	10	7%	0%	6%	1%
Lagoon 6	Downwind	25	3	10	4	5	6	10	5%	0%	4%	1%
Lagoon 7	Downwind	25	3	10	10	5	6	10	5%	0%	4%	1%
Lagoon 8	Downwind	25	3	10	2	25	6	10	9%	0%	3%	6%
Lagoon 9	Downwind	25	3	10	2	50	6	10	14%	0%	4%	10%

Table 5. Model scenarios and results the understorey source. The green shaded boxes show the sets of varied parameters that are being compared.

Model scenario	Design	Main canopy length (m)	LAI	Height(m)	LAD Profile	Back-stop length (m)	LAI	Canopy height (m)	% Total deposited	% Deposited upwind of the main canopy (x_{c0}	% Deposited in main canopy (x_{c1})	% Deposited in back-stop (x_{c2})
Understorey 1	Symmetrical	100	3	10	0	0	—	—	15%	0%	15%	0%
Understorey 2	Symmetrical	100	3	10	0	5	6	10	17%	0%	15%	2%
Understorey 3	Symmetrical	100	3	10	0	10	6	10	20%	0%	16%	4%
Understorey 4	Symmetrical	100	3	10	0	25	6	10	28%	0%	20%	8%
Understorey 5	Symmetrical	100	3	10	0	50	6	10	37%	0%	24%	13%
Understorey 6	Symmetrical	100	6	10	0	50	6	10	60%	0%	51%	9%
Understorey 7	Symmetrical	100	6	10	1	50	6	10	49%	0%	45%	4%
Understorey 8	Symmetrical	100	6	10	2	50	6	10	24%	0%	22%	2%

Table 6. Changes in deposition capture in the canopy throughout the year with RH kept constant.

Monthly variation in the deposition	Deposition in the main canopy %	Deposition in backstop %	Total deposition %	LAI Main canopy m² m⁻²	LAI Backstop m² m⁻²	PAR W m⁻²	Ta °C	RH %	Wind speed m s⁻¹
January	1.0%	13.9%	14.9%	0.5	6.0	134	2.2	90	5.7
February	1.0%	13.6%	14.6%	0.5	6.0	201	1.3	90	5.9
March	1.1%	15.1%	16.2%	0.5	6.0	340	3.1	90	4.9
April	1.9%	14.0%	15.9%	1.0	6.0	516	4.7	90	5.1
May	4.5%	13.4%	17.9%	3.0	6.0	668	6.1	90	5.8
June	5.4%	15.0%	20.4%	3.0	6.0	790	8.2	90	4.5
July	5.9%	15.8%	21.7%	3.0	6.0	628	8.5	90	4.0
August	7.1%	17.4%	24.5%	3.0	6.0	616	7.8	90	3.1
September	6.8%	17.0%	23.8%	3.0	6.0	418	7.5	90	3.3
October	2.3%	12.4%	14.7%	1.5	6.0	271	6.7	90	6.3
November	1.0%	14.1%	15.1%	0.5	6.0	132	2.5	90	5.6
December	1.0%	13.5%	14.5%	0.5	6.0	87	1.3	90	5.9

Table 7. Changes in deposition capture in the canopy throughout the year with varying RH.

Monthly variation in the deposition	Deposition in the main canopy %	Deposition in backstop %	Total deposition %	LAI Main canopy m² m⁻²	LAI Backstop m² m⁻²	PAR W m⁻²	Ta °C	RH %	Wind speed m s⁻¹
January	1.2%	16.0%	17.2%	0.5	6.0	134	2.2	100	5.7
February	1.1%	15.7%	16.9%	0.5	6.0	201	1.3	100	5.9
March	1.1%	15.1%	16.9%	0.5	6.0	340	3.1	90	4.9
April	1.5%	11.7%	13.3%	1.0	6.0	516	4.7	80	5.1
May	2.9%	9.4%	12.3%	3.0	6.0	668	6.1	70	5.8
June	3.1%	9.6%	12.7%	3.0	6.0	790	8.2	60	4.5
July	3.2%	9.6%	12.8%	3.0	6.0	628	8.5	50	4.0
August	4.1%	11.1%	15.2%	3.0	6.0	616	7.8	50	3.1
September	4.1%	11.4%	15.6%	3.0	6.0	418	7.5	60	3.3
October	1.8%	10.2%	12.0%	1.5	6.0	271	6.7	80	6.3
November	1.0%	14.1%	15.1%	0.5	6.0	132	2.5	90	5.6
December	1.1%	15.7%	16.8%	0.5	6.0	87	1.3	100	5.9

velocity on the main canopy allowing a longer residence time and hence a better recapture efficiency. However, main canopies with high LAIs (e.g. LAI 6) also capture significant amounts of ammonia making the necessity for backstop structures less critical. The canopy with a dense and homogeneous LAD favours deposition (LAD 10), while a canopy with a dense crown and an open trunk space is less effective at recapture. However, for the under-storey scenario such dense canopies are not realistic due to the need for livestock to be able to freely roam under the canopy. Therefore the optimal canopy structure for housing and under-storey livestock systems are not the same.

The model behaves consistently with regard to changing the source strength. This means that, in the model, the percentage of ammonia that is recaptured is independent of the source strength. This makes the model adaptable for most farm scenarios making it an effective tool for calculating tree recapture.

Sensitivity analysis has shown that there is a reduction in the recapture efficiency during the winter months for deciduous trees but importantly the coniferous backstop continues to recapture ammonia throughout the year. The most sensitive parameter in the model is the RH showing reductions in recapture during the summer months for both deciduous and coniferous trees. Further analysis is required to test the effect of other relations which can lead to improvements in future versions of the model.

Specifically the optimal housing systems would have a woodland length of mixed LAI of canopy of around 75 m to achieve a deposition rate or recapture efficiency of 25%. A less dense main canopy of around 25 m and a backstop of 50 m match this objective. Slurry lagoons systems are also suited to dense canopy structures near to the ground as the source is very close to the ground. 30 m dense stands can achieve recapture efficiencies of up to 20%. For under-storey systems with free-range chickens a less dense canopy
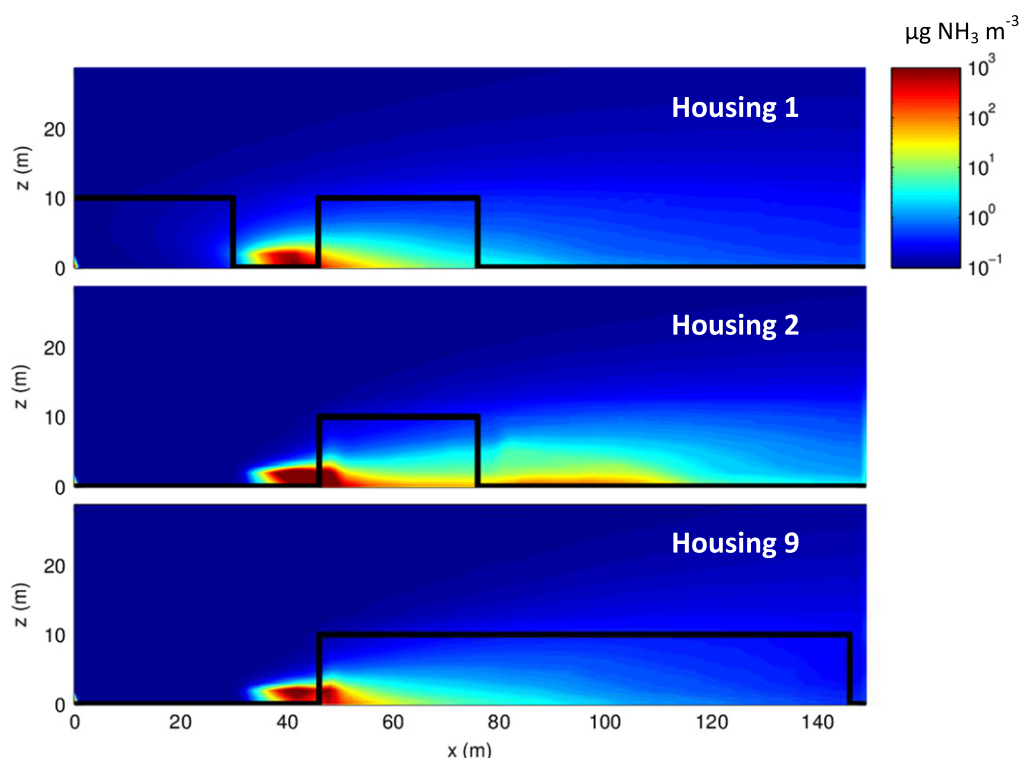
Figure 6. Output from MODDAS-THETIS showing the concentration field in the 'Housing' source runs from the top—scenario Housing 1, Housing 2 and Housing 9. The black line outlines the canopy structure.
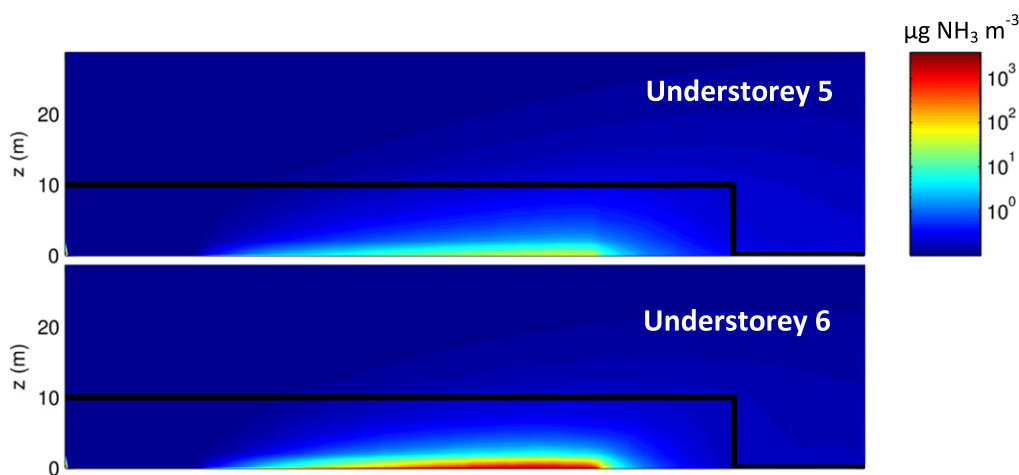

Figure 7. Output from MODDAS-THETIS showing the concentration field in 'under-storey' model runs Understorey 5 (upper panel) and Understorey 6 (lower panel) with varying LAI 3 and 6 $m^2\,m^{-2}$ respectively.

structure (LAI = 3 and LAD-2) is required to allow the chickens to roam freely and use areas of dappled sunlight. Furthermore, due to the welfare targets of a maximum of 0.25 birds per metre square for free-range birds, much larger areas of woodland are required to cater for even fairly small flocks. In our scenario 2500 birds can be enclosed in a hectare of forest (100 m × 100 m). With a 100 metre main canopy for the birds to roam under (LAI = 3) and a 25 m dense backstop (LAI-6), a 40% recapture efficiency should be attainable with current scenarios.

There are over 1000 IPPC permits in England for pig and poultry installations alone, some of which represent large 'hot spots' of ammonia emissions. Many sensitive ecosystems and protected sites are relatively close to these hot spots (<200 m). Hence ammonia abatement through agro-forestry systems is a relatively simple approach to mitigate some of the impacts of ammonia in the landscape. The measures would compliment source mitigation options.

This work has provided the first qualitative scenario modelling, building on work by Theobald *et al* (2004), and
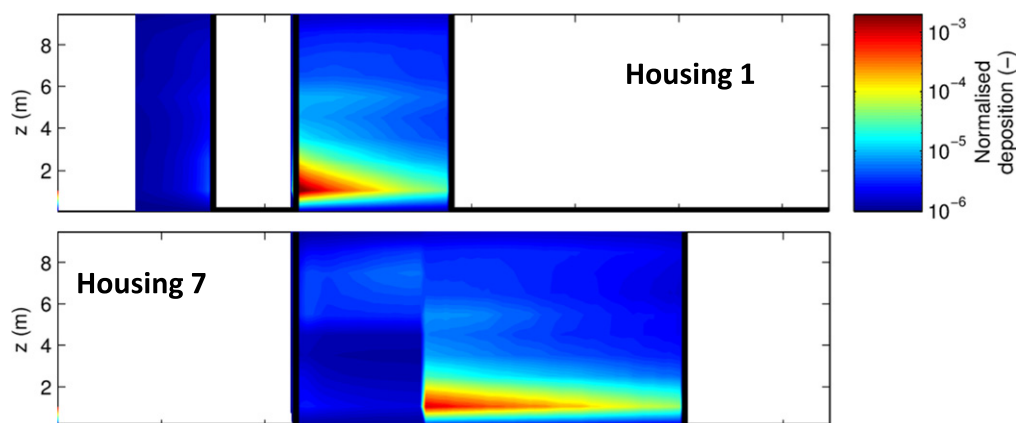
Figure 8. Output from MODDAS-THETIS showing the deposition patterns in Housing 1 and Housing 7. The colours show NH_3 deposition to the canopy normalized by the source strength. The lower panel shows the scenario with the backstop located at 70 m. The maximum colour-scale is 2.10^{-3}.
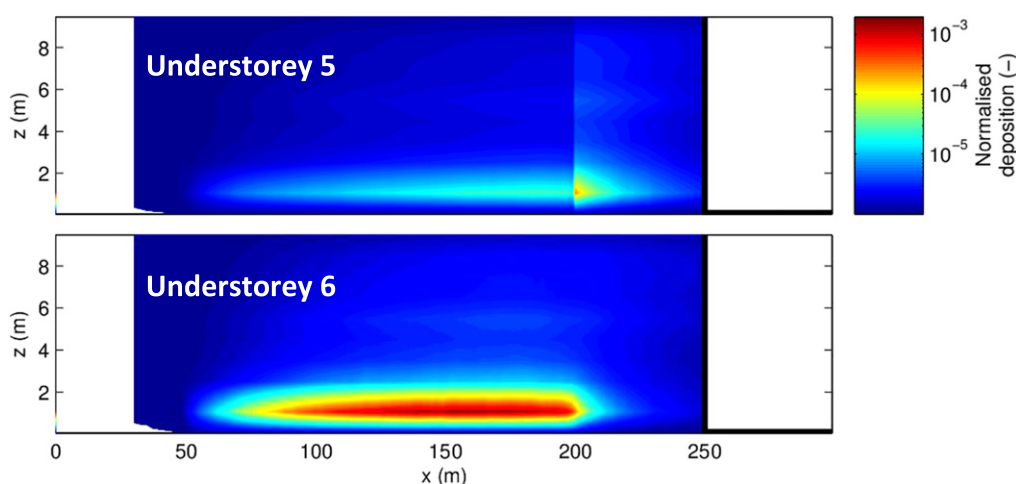

Figure 9. Output from MODDAS-THETIS showing the deposition patterns in the understorey model runs—Understorey 5 (upper panel) showing the effect of the backstop with an open main canopy (LAI 3), and Understorey 6 (lower panel) showing the effect of a dense main canopy (LAI 6). The deposition is normalized by dividing by the source strength. The maximum colour-scale is 2.10^{-3} as in figure 8.

provides a basis for developing better tools to plan on-farm abatement measures.

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