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2016. **The potential for tree planting strategies to reduce local and regional ecosystem impacts of agricultural ammonia emissions**.

The potential for tree planting strategies to reduce local and regional ecosystem impacts of agricultural ammonia emissions

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Abstract

Trees are very effective at capturing both gaseous and particulate pollutants from the atmosphere. But while studies have often focussed on PM and NOx in the urban environment, little research has been carried out on the tree effect of capturing gaseous emissions of ammonia in the rural landscape. To examine the removal or scavenging of ammonia by trees a long-range atmospheric model (FRAME) was used to compare two strategies that could be used in emission reduction policies anywhere in the world where nitrogen pollution from agriculture is a problem. One strategy was to reduce the emission source strength of livestock management systems by implementing two 'tree-capture' systems scenarios – tree belts downwind of housing and managing livestock under trees. This emission reduction can be described as an 'on-farm' emission reduction policy, as ammonia is 'stopped' from dispersion outside the farm boundaries. The second strategy was to apply an afforestation policy targeting areas of high ammonia emission through two planting scenarios of increasing afforestation by 25% and 50%. Both strategies use trees with the aim of intercepting NH_3 *emissions to protect semi-natural areas. Scenarios for on-farm emission reductions showed national reductions in nitrogen deposition to semi-natural areas of 0.14% (0.2 kt N-*NH_x*) to 2.2% (3.15 kt N-*NH_x*). Scenarios mitigating emissions from cattle and pig housing gave the highest reductions. The afforestation strategy showed national reductions of 6% (8.4 kt N-*NH_x*) to 11 % (15.7 kt N-*NH_x*) for 25% and 50% afforestation scenarios respectively. Increased capture by the planted trees also showed an added benefit of reducing long range effects including a decrease in wet deposition up to 3.7 kt N-*NH_x* (4.6%) and a decrease in export from the UK up to 8.3 kt N-*NH_x* (6.8%).*

Introduction

By 2020, it is estimated that ammonia will be the largest single contributor to the nutrient nitrogen and acid deposition, and secondary particulate matter formation in Europe (Reis *et al.*, 2015). Emissions in Ammonia (NH_3) have increased substantially during the 20th century. Globally since 1970, world population has increased by 78% and reactive nitrogen creation has increased by 120% through the intensification of agriculture including fertiliser use and livestock production (Galloway *et al.*, 2008). By 2050 the global emission of reactive nitrogen is projected to be 200 Tg N yr, while back in 1860 it was estimated at 34 Tg N yr-1 (Galloway *et al.*, 2004). Environmental impacts from nitrogen and particular ammonia are caused by the loss or leakage of reactive nitrogen as it is volatilized into the atmosphere. Bouwman *et al.* 2002 estimated that NH_3 loss from global application of synthetic N fertilizers accounts for 78 million tons N per year, and animal manure 33 million tons N per year, amounting to 14% and 23% losses respectively.

In the UK, agricultural practises currently accounts for over 80% of NH_3 emissions (Sutton, *et al.*, 2001; Misselbrook *et al.*, 2010). Four main categories of agricultural management activities can be identified as key sources of ammonia: emissions from housing, grazing, storage and manure spreading, and fertiliser use (Misselbrook *et al.*, 2010). Ammonia emissions at the local scale vary greatly within the landscape and dry deposition of ammonia occurs especially close to sources (Hellsten *et al*., 2008; Dragosits *et al.*, 2002). As a consequence, nitrogen sensitive ecosystems close to sources are at a high risk of negative impacts. Impacts of excess nitrogen can include eutrophication and acidification effects which can lead to species composition changes (Bobbink *et al.*, 2010; Pitcairn *et al.*, 1998; Sheppard *et al.*, 2008; Van den Berg *et al.*, 2008; Wiedermann *et al.*, 2009) and other deleterious effects. Species adapted to low N availability are at a greater risk; for example, many slower-growing lower plants, notably lichens and bryophytes. (Pearce and van der Wal, 2002; Bobbink *et al.*, 2010).

A large number of abatement methods already exist for reducing ammonia emissions from agriculture (Bittman *et al.*, 2014). These include animal housing techniques like drying manure, decreasing the surface area fouled by manure and 'scrubbing' ammonia from the exhaust air of livestock houses; livestock feeding strategies where low-protein feeding is carried out; improving manure storage through covering and encouraging crusting; and using low emission manure spreading through injection or band application. Alternative options like agro-forestry have received less attention and pollution regulators and the livestock industry are increasingly interested in alternative abatement techniques that reduce the effects of nitrogen deposition on nearby protected sites.

Trees are very effective at capturing both gaseous and particulate pollutants from the atmosphere (Beckett 2000; Nowak, 2000; Novak *et al.* 2014; McDonald *et al.*, 2007; Cohen *et al.*, 2014). Deposition rates are far greater to forest than those of short vegetation e.g. grassland, by a factor of 3–20 times (Gallagher *et al*, 2002; Fowler *et al.*, 2004). However, most studies up till now have focused on gases and particulates (e.g. NO_x, $PM_{10}/_{2.5}$) in relation to improving urban air quality. There is a paucity of studies examining the capability of trees to capture ammonia from agricultural sources to protect sensitive habitats. Converting agricultural grassland or arable land to trees near emission sources can be seen as a way to increase the removal of ammonia from the atmosphere, thereby reducing the potential impacts on nearby sensitive ecosystems.

To examine this removal through scavenging of ammonia by trees across the UK, a Lagrangian national-scale atmospheric dispersion model (FRAME) was used to compare two strategies:

1. The first strategy (Strategy A) estimated the potential effectiveness of implementing local, on-farm, tree planting schemes to capture ammonia. One planting scheme was to place tree belts downwind of animal housing and storage facilities; the other planting scheme was to provide trees as shelter for livestock managed under the trees.
2. The second strategy (Strategy B) was to apply a general afforestation policy across the UK by increasing tree planting, targeting areas of high ammonia emissions.

Methodology

The first approach for reducing on-farm emissions (Strategy A) was to make use of existing estimates of percentage NH_3 recapture from trees downwind of housing and storage systems (20%), and percentage NH_3 recapture from trees with the livestock managed under the trees (45%). Using these recapture percentages a set of revised emission factors for all livestock types and management systems were developed. Finally, with these new 'on-farm' emission factors eight different scenarios (A_1 to A_8) were designed for testing with the FRAME model.

Although the reduction in Strategy A is actually associated with the trees capturing ammonia, this was implemented in the model by modifying the emission factors of each livestock type instead. In effect, the emission reduction occurs as a reduction of the whole on-farm system for a constant unit output, as ammonia is captured before being dispersed outside the 'farm boundaries'.

To assess the influence of a general afforestation strategy (Strategy B) on the re-capture of ammonia, three land cover scenarios were tested in the model. These consisted of the baseline scenario (B_0) and two planting scenarios – increasing total forest cover by 25% (B_1) and 50% (B_2), respectively, across the UK. In addition to this, tree planting was targeted near emission sources where ammonia concentrations are highest and thus maximise re-capture potential. Only arable and grassland were converted to forests, with the other land cover categories (e.g. moorland and urban) remaining unchanged. Tree cover was increased by scaling the existing forest cover in model grid squares targeted due to high levels of ammonia emissions (or by adding new forest in grid squares with no tree covers).

To summarise, the key steps were to generate new emission factors for agro-forestry systems (Strategy A) and increased tree cover scenarios (Strategy B) for application in an atmospheric transport model, taking into account the effect of NH_3 recapture by trees.

In both scenarios it should be noted that the FRAME model does not take into account deposition to different tree species. Dry deposition is calculated to 5 land classes of which forest is one (arable, forest, moor-land, grassland and urban). For ammonia, deposition is calculated for each grid square using a canopy resistance model (Singles *et al.*, 1998). Deposition velocities are therefore generated from the sums of the aerodynamic resistance, the laminar boundary layer resistance and the surface resistance as well as the geographical and altitudinal variation of wind-speed.

The following sections describe the methodology in more detail.

Atmospheric dispersion modelling

The FRAME (Fine Resolution Atmospheric Multi-species Exchange) model (Singles *et al.*, 1998; Fournier *et al.*, 2003; Dore *et al.*, 2007; *Vieno et al.*, 2007; Dore *et al.*, 2012) was applied at a 1 km grid resolution across the British Isles to assess the influence of both abatement strategies on ammonia concentrations in air and the deposition of reduced nitrogen. FRAME is a Lagrangian atmospheric transport model developed to output annual mean deposition of reduced and oxidised nitrogen and sulphur. The model uses rainfall and wind speed inputs, (Dore *et al.*, 2006) as well as emission and land cover data and has been used to assess the environmental impact of nitrogen deposition (Matejko et al., 2009). FRAME has been used to model pollutant deposition over Europe, the UK, Poland and parts of China.

FRAME at the 1km grid resolution has been used to assed critical level exceedance of ammonia over the UK's Natura2000 sites (Special Protection Areas and Special Areas of Conservation) (Hallsworth *et al.* (2010)).

This study uses emission data from the 2008 National Atmospheric Emissions Inventory (NAEI) for SO_2, NO_x and non-agricultural NH_3. For agricultural NH_3, the Atmospheric Emissions for National Environmental Impacts Determination (AENEID; used for annual UK maps for the NAEI; Dragosits et al. 1998; Hellsten et al. 2008) was used for developing the detailed emission scenarios. The AENEID model redistributes agricultural emissions across the landscape by weighting the source strength of five broad management activities - livestock grazing, livestock housing, manure storage, land-spreading of manures and mineral fertiliser application. Emission source strength data (emission factors) are calculated annually for the UK agricultural emission inventory (Misselbrook *et al.* 2010). The spatial distribution of ammonia emissions from agricultural sources for 2008 is illustrated in Figure 1.

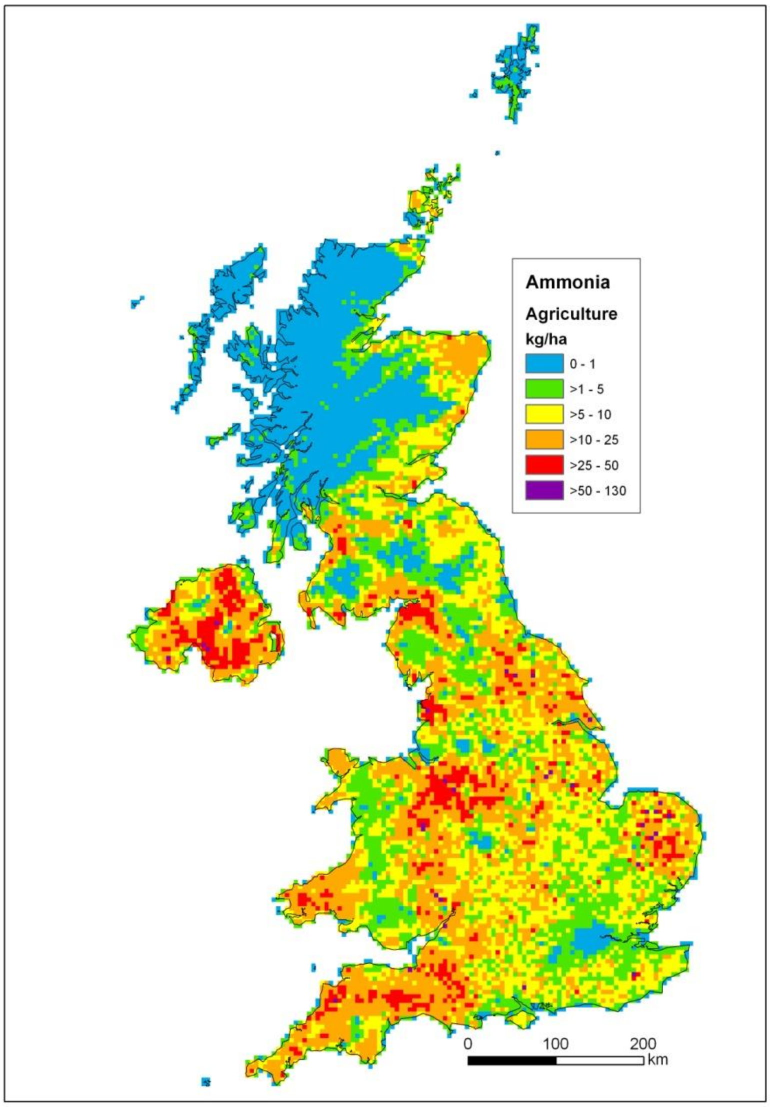


Figure 1: Emissions of ammonia from agricultural sources in the UK for the year 2008 (5 km grid resolution).

Strategy A - Revision of 'on-farm' emission factors

In a prior analysis we used the *MODDAS-THETIS* model to assess the optimum tree canopy structures for capturing ammonia from livestock farms (Bealey *et al.* 2014 in press). We assessed three farm management practices – NH_3 emissions from housing, slurry lagoons, and livestock living under the tree canopy. By changing model parameters such as width of canopy, leaf area index and leaf area density, optimal tree structure configurations for capturing ammonia were established for each management practice. The capture efficiencies represent the extra amount of ammonia deposited in the tree canopy that would not have been deposited if the tree canopy had not been there. It is therefore an extra deposition above what would normally deposit at this distance from a farm if the land-use was not changed to trees (e.g. grassland or arable crops).

The following percentage NH_3 capture efficiencies were then used to recalculate the livestock emission factors for use in the modelling:

- 20% NH_3 capture efficiency for housing emissions which were representative of a 10m tall tree canopy, with a 25 m long main canopy (LAI 3) and a 25 m dense backstop canopy (LAI 6).

- 20% NH_3 capture efficiency for storage emissions which were representative of a 10m tall tree canopy, with a 30 m long main canopy (LAI 6).
- 45% NH_3 capture efficiency for livestock under-canopy silvo-pastoral farming systems (i.e. grazing emissions) which were representative of a 10m tall tree canopy, 100 m main canopy (LAI 3), and a 50 m dense backstop canopy (LAI 6)

In order to parameterise this effect in the FRAME model reduced emission factors were calculated for each livestock type. Table 1 shows the calculations of revised emission factors for the key livestock types.

For laying hens, a number of tree belt options were considered. This included a basic option to provide a tree shelter belt downwind of the housing to capture ammonia (i.e. 20% housing emission reduction). The option of having free-range laying hens under a tree canopy was also calculated (45% grazing emission reduction), with a final advanced option of having both the housing (in the form of small arks) covered with a tree belt, and free-range laying hens under the tree canopy. This system gave a reduction in the 'on-farm' emission factors of both the housing and grazing by 45% each. For other poultry types the same calculations were carried out to derive reduced emission factors. This included broilers, turkeys, pullets (young laying hens), and a summary category of 'other poultry' (which includes, ducks, geese, guinea fowl and other species less common in the UK).

For sows, around 36% of the herd are kept outdoors already. Therefore emission reduction was calculated based on doubling this to 72%, with the pigs also living under the tree canopy. This gave a 45% reduction in the grazing emission factor, and at the same time a reduction in the housing emission factor. This process was repeated for other pig categories.

For cattle, a similar approach was taken as for the laying hens. Reduced emission factors using trees to capture housing and slurry storage emissions were calculated. Cattle grazing under trees as a management system were not considered for an emission-factor reduction, mainly due to the requirement for very low stocking densities. However, cattle grazing under trees are used for conservation reasons and are deployed by many conservation organisations (Armstrong *et al.*, 2003).

Table 1: *Emission factor reductions for livestock types using two tree planting scenarios, of 45% for grazing under trees, and 20% for planting trees around housing and manure storage units. The full table can be seen in Annex: Table A1.*

Livestock Type	Management System	Housing $\%NH_3$ Capture Efficiency	Grazing $\%NH_3$ Capture Efficiency	Storage $\%NH_3$ Capture Efficiency	Current (2008) total Emission Factor	Revised total Emission Factor	Total % emission reduction
Laying hens	In housing upwind of tree belt, no ranging	20%	0%	0%	0.264	0.233	**12%**
Laying hens	In housing upwind of tree belt + 25% ranging* under trees	20%	45%	0%	0.264	0.194	**27%**
Laying hens	In housing under tree canopy (arks) + 25% ranging* under trees	45%	45%	0%	0.264	0.165	**38%**
Sows	Double the number of sows outdoors (currently 36%) + ranging under trees	0%	45%	0%	5.242	2.844	**46%**
Other pigs >80-110 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	45%	0%	5.310	4.857	**9%**
Other pigs >50-80 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	45%	0%	4.580	4.180	**9%**
Other pigs >20-50 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	45%	0%	3.060	2.815	**8%**
Dairy cows & heifers	In housing upwind of tree belt, no ranging + slurry store with trees downwind	20%	0%	20%	26.173	22.688	**13%**

* The 25% ranging value was calculated based on personal communication from poultry farmers

Scenario modelling

For Strategy A the revised emission factors were applied to eight scenarios covering all livestock types with the aim of showing the benefit of using trees for reducing emission source strength. The scenarios were:

- A_1: applied to 50% of the UK poultry flock trees downwind of their housing.
- A_2: 37% of the laying flock (currently the number which is free-range in the UK) were put under trees and at the same time their housing was sheltered with tree belts.
- A_3: of the 37% free-range poultry, 30% had their housing placed under the tree canopy (in arks).
- A_4: 50% of the entire UK poultry flock (around 110 million birds) had their housing sheltered with tree belts while a further 10% were allowed to range under the tree canopy.
- A_5: a combination of Scenarios A_1-A_4,
- A_6: made 20% of all cattle housing and their associated manure storage to be sheltered by trees.
- A_7: doubling (to 72%) the proportion of sows living outdoors and providing trees as shelter, 15% of the pigs were put outdoors under trees.
- A_8: a combination of Scenarios A_5, A_6 and A_7 to model the effect of a large scale implementation of grazing livestock under trees and sheltering their housing and manure storage with tree belts.

For Strategy B - national scale afforestation scenarios - a summary of the scenarios is given below:

- B_0 – baseline scenario
- B_1 – increasing total forest cover by 25%
- B_2 – increasing total forest cover by 50%

Results and Discussion

Strategy A: 'On-farm' emission source strength reductions

Table 2 summarises the percentage change in emissions based on the scenario descriptions above for the three main livestock types. The total change in NH_3 emissions across the whole livestock sector and as a percentage change across the UK was calculated. A full list of emission changes for each scenario can be found in the Annex: Table A2.

***Table 2**: Summary table showing the percentage change in NH_3 emissions across individual livestock types, total livestock as a whole, and the overall change in UK NH_3 emissions from all sources.*

% change					
	cattle	pigs	Poultry % (kt NH_3)	total livestock %	total national NH_3 emission %

A_1	-	-	-4.2% (1.3)	-0.7%	-0.5%
A_2	-	-	-2.5% (0.8)	-0.4%	-0.3%
A_3	-	-	-2.9% (0.9)	-0.4%	-0.3%
A_4	-	-	-1.9% (0.6)	-0.3%	-0.2%
A_5	-	-	-8.3% (2.6)	-1.3%	-0.9%
A_6	-2.6% (3.4)	-	--	-1.7%	-1.2%
A_7	-	-12.6% (2.5)	-	-1.3%	-0.9%
A_8	-2.6% (3.4)	-12.6% (2.5)	-8.3% (2,5)	-4.3%	-3.0%

Emission changes from carrying out partial, but fairly wide scale abatements e.g. A_1 putting trees downwind of half the poultry sheds in the UK results in only a small national reduction in ammonia emissions of 1,293 tonnes of NH_3. This is largely due to the small emission factor for poultry. The emissions are doubled with scenario A_5 where all scenarios A_1-A_4 were applied. The A_5 scenarios resulted in a 8.3% reduction in poultry emissions (2.6 kt). Applying tree planting around 20% or cattle sheds and storage resulted in a 2.6% reduction to total cattle emissions representing 3.4 kt of ammonia captured nationally. Doubling the pig population to outdoors gave 12.6% reduction representing 2.5 kt recaptured by the trees. The final scenario combined all livestock scenarios (A_1-A_7) and provided the highest emission reductions (8.4 kt, 4.3% of the total livestock population). Nationally the percentage reductions are small (0.5% to 3%) with respect to the total emissions. One might conclude that quite a lot of tree planting is required for small gains, but that tackling the largest emitters (e.g. cattle and pigs) should be the main target for reducing emissions. However, applying a combination of scenarios as set out in A_8 can significantly reduce emissions below future 2020 threshold limits set by UNECE (UNECE, 2012) or in Europe by the National Emissions Ceiling Directive (NECD) (Council Directive 2001/81/EC). Figure 2 shows the emission scenarios (A_1-A_8) including the current temporal trend (blue line) and the resulting emissions each scenario could achieve by 2030. 2030 was chosen as a suitable future year to achieve realistic growth and size of tree assuming trees were planted by 2020. The UNECE 2020 target for NH_3 in the UK is 283 kt of NH_3 and Figure 2 shows that by applying scenario A_8 this target can be achieved even by 2020.

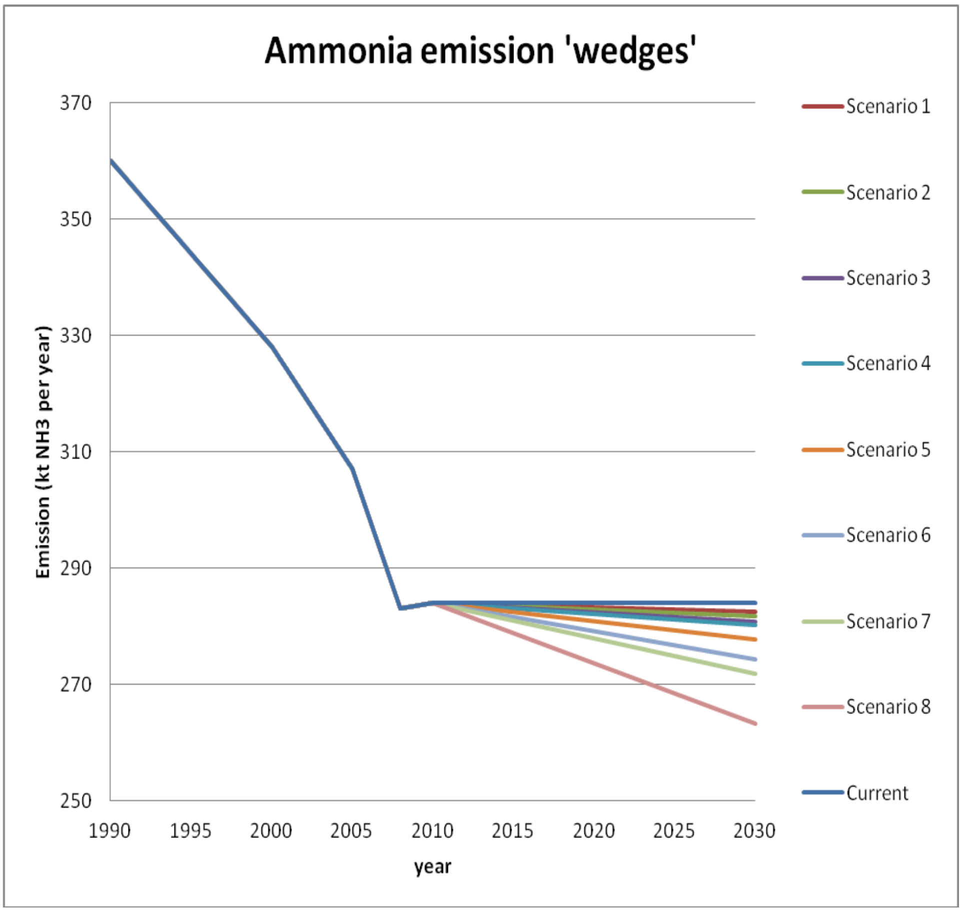


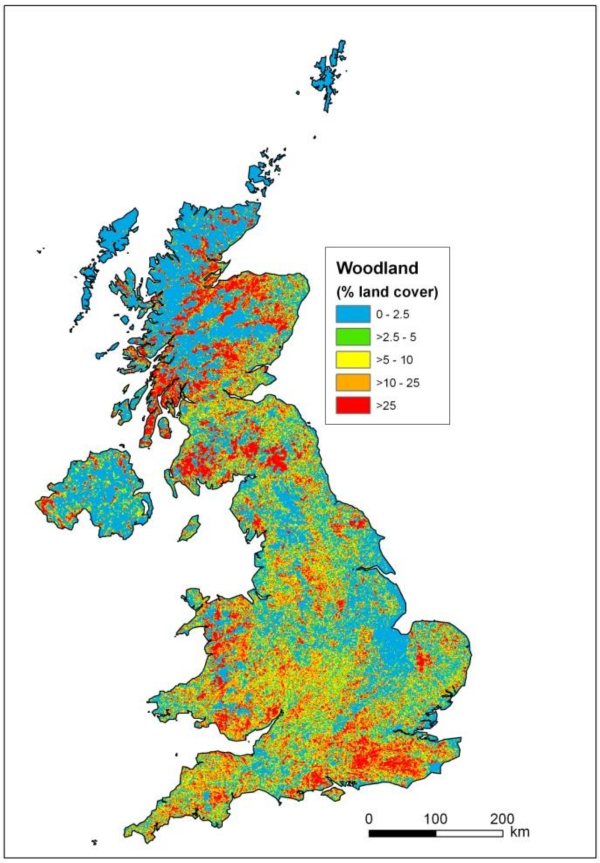
Figure 2: *Emission scenarios (A1-A8) including the current trend (blue line) and the resulting emissions each scenario could achieve by 2030 for the UK. The emissions are cumulative.*

Strategy B: national scale afforestation scenarios

A summary of the changes to land cover is illustrated in Table 3. Arable and grassland land cover was reduced for scenarios B1 and B2 to accommodate introduction of new tree plantings in targeted areas of high ammonia emissions. The spatial distribution of forest cover for the baseline scenario and the change between the baseline and the +50% scenario are illustrated in Figure 3. 11.7% of forest in the UK represents around 2.8 million hectares.

Table 3. *Percentage of land cover types for the baseline and 25% and 50% afforestation scenarios.*

SCENARIO	arable	forest	Grass	semi-natural ecosystems	urban	water
B_0 BASELINE	23.0	11.7	22.3	33.8	6.6	2.6
B_1 + 25%	21.7	14.7	20.6	33.8	6.6	2.6
B_2 + 50%	20.4	17.6	19.0	33.8	6.6	2.6



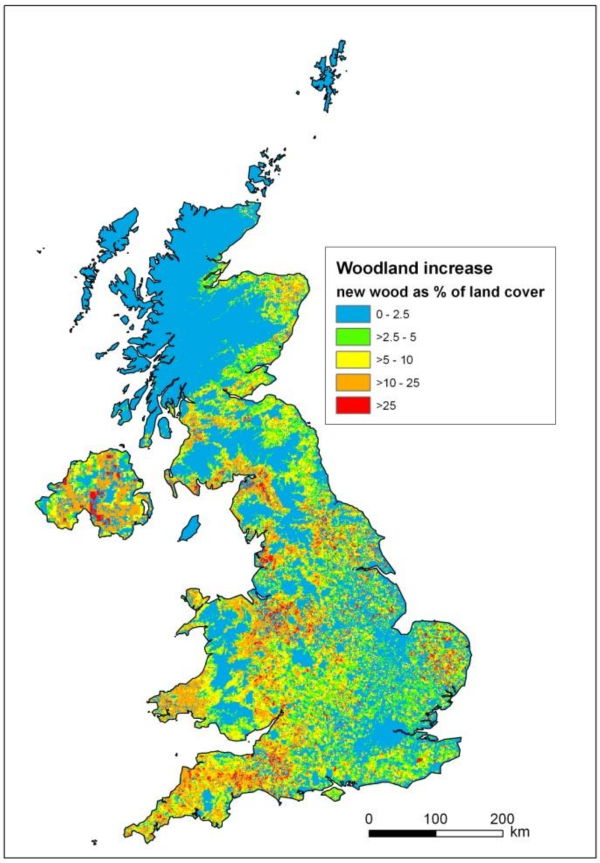


Figure 3: *Forest distribution in the UK. Percentage of land cover which is woodland for the baseline scenario (left); Percentage of land which is new woodland for the +50% scenario (right)*

Atmospheric dispersion modelling

Strategy A

Table 4 shows the percentage reduction in nitrogen deposition for each scenario across the UK. Scenarios 1-4, covering the poultry sector, show small reductions in total nitrogen deposition even though the woodland systems were applied to over half, in some cases, of the total UK flock. This is due to the low emission factor for poultry as a whole, even though there are over 160 million birds in the UK. However, Scenario A5 (all poultry scenarios 1-4 are included) has a higher reduction of 0.62%. For the cattle sector a total NH_3 emission reduction of 0.95% is achievable with placing woodland structures around 20% of the cattle housing around the UK and 20% of the slurry stores. Doubling the number of outdoors sows together with foraging under trees (36% to 72%) and putting a percentage (15%) of other pigs under trees reduces N deposition by 0.64%. The best reduction in total nitrogen deposition is achieved by the combination of all scenarios, at 2.2%.

Table 4*: Percentage change in total nitrogen deposition from each emission reduction scenario*

SCENARIOS	% (kt N-NHx) reduction in total N (grid average)
SCENARIO A1 POULTRY - 50% of all poultry houses sheltered	0.3% (0.45)
SCENARIO A2 POULTRY - housing sheltered and foraging under trees	0.2% (0.28)

SCENARIO A3 POULTRY - Birds ranging under trees, 70% houses sheltered, 30% in arks under trees	0.2% (0.3)
SCENARIO A4 POULTRY - broilers (60% houses sheltered, 10% forage under trees)	0.14% (0.2)
SCENARIO A5 POULTRY (combination of Runs 1-4)	0.62% (0.9)
SCENARIO A6 Dairy+ Beef (20% of cattle houses and slurry stores sheltered)	0.95% (1.35)
SCENARIO A7 PIGS (72% of sows and 15% of other pigs foraging under trees)	0.64% (0.91)
SCENARIO A8 COMBO (SC5 Poultry, SC6 Cattle and SC7 Pigs)	2.2% (3.15)

For all scenarios both wet deposition and export of nitrogen deposition from the UK are reduced since more ammonia is captured in the tree canopy by dry deposition processes. The A_8 scenario resulted in a 2% reduction in both wet deposition (1.5 kt N-NH_x) and export (3.3 kt N-NH_x) compared to the base run.

Strategy B

The national reduced nitrogen (NH_x) budget for the three scenarios is illustrated in Table 5. The two tree planting scenarios (25%, 50%) result in significant changes to the fate of emitted ammonia, resulting not only in significant increases in dry deposited NH_x (to forest) and decreases in wet deposited NH_x, but also in decreased export of NH_x in air leaving the UK (which contributes to the long range transport of air pollution in Europe). Changes in NH_x deposition and export for tree planting scenarios B1 and B2 are expressed as percentages relative to the baseline scenario. It can be seen that the influence of a 50 % national scale increase in forest cover in the UK targeted at high ammonia emissions areas would result in a 19.5% increase in total dry N deposition, a decrease of 4.6% in total wet N deposition and a 6.8% decrease in the export of reduced nitrogen from the UK.

Table 5: *The UK mass deposition and export budgets for simulations B_0, B_1 (+25%) and B_2 (+50%) showing reductions in dry, wet and total nitrogen deposition.*

Gg N-NH_x	**B_0 BASELINE**	**B_1 + 25% forest**	**B_1 reduction (%) + 25% forest**	**B_2 + 50% forest**	**B_2 reduction (%) + 50% forest**
Dry Deposition	61.5	68.0	6.4 (10.4%)	73.5	12 (19.5%)
Wet Deposition	81.1	79.1	-2 (-2.4%)	77.4	-3.7 (-4.6%)
Total Deposition	142.6	147.1	4.5 (3.2%)	151.0	8.4 (5.9%)
Export	121.4	116.9	-4.5 (-3.7%)	113.1	-8.3 (6.8%)

The results from FRAME for the baseline scenario for ammonia concentration in air as well as deposition of reduced nitrogen are illustrated in Figure 4.

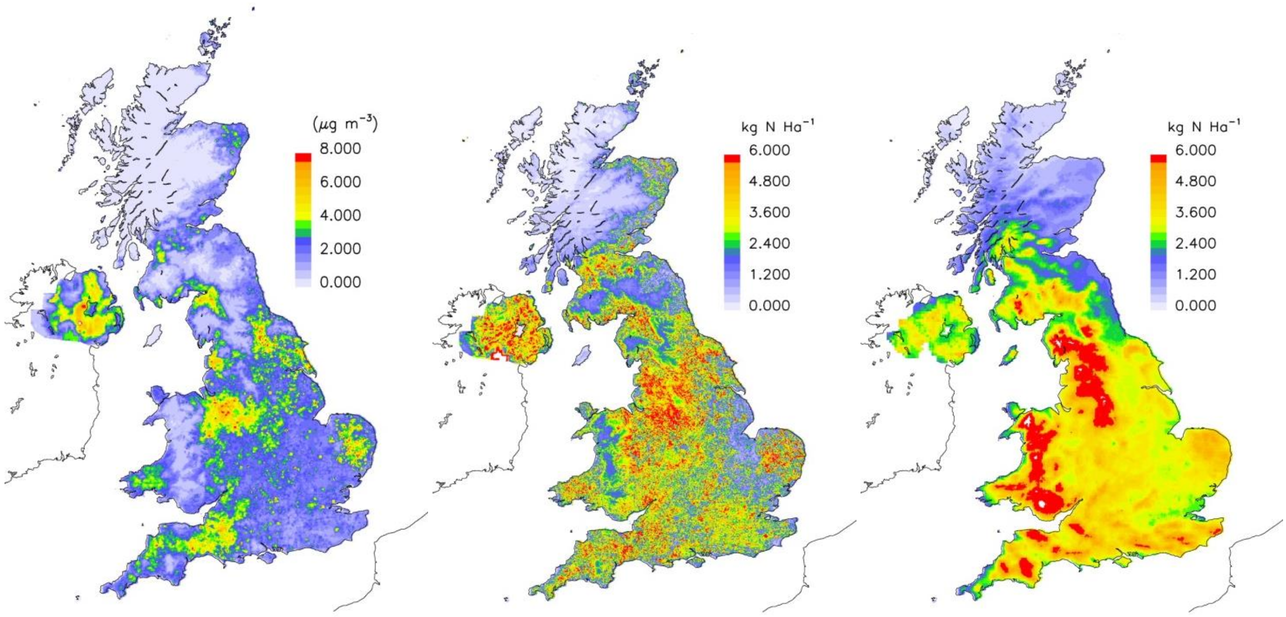


Figure 4. *Baseline Scenario: Modelled concentration of NH_3 in air (left); Dry deposition of NH_x (middle); Wet deposition of NH_x (right)*

Agricultural ammonia concentrations in the UK are highest across areas of cattle farming in the western parts of the country (in particular NW, W and SW England, SW Wales and Northern Ireland), as well as in localised hot spots around intensive pig and poultry farms (mainly NE and E England). This distribution is closely reflected in the patterns of dry deposition of NH_x, which is primarily due to the deposition of locally emitted ammonia gas. A different pattern is evident for wet deposition of NH_x, due to the chemical transformation of ammonia gas to ammonium aerosol and resulting long range transport. Wet deposition is highest in the high precipitation upland areas of Wales and the Northern England.

The modelled scenarios with increased woodland led to an increase in NH_x dry deposition near the emission sources (12 kt N-NH_x (19.5%)) due to the lower canopy resistance of forest compared to the land cover types which it replaced (grassland and arable). The reduced availability of ammonia gas in the atmosphere away from emission sources therefore resulted in decreases in NH_x wet deposition and in NH_x dry deposition to sensitive ecosystems.

Figure 5 illustrates the decrease in NH_x deposition resulting from implementation of scenario B (50% national increase in forest cover). Significant reductions in nitrogen deposition were achieved with this scenario. In areas of high wet deposition (the NW England and Wales), the reduction in wet deposition was up to 0.5 kg N ha^{-1} yr^{-1}. Higher decreases of up to 2 kg N ha^{-1} yr^{-1} for dry deposition were achieved for large areas of semi-natural land and forest. While the deposition per unit area of forest decreased, it is important to note that total mass of NH_x deposited to forest increased due to the national increase in forest area. This is generally considered to be beneficial, as deposition would be directed to the new plantation forests in agricultural areas, consequently reducing the impact on established semi-natural forest ecosystems.

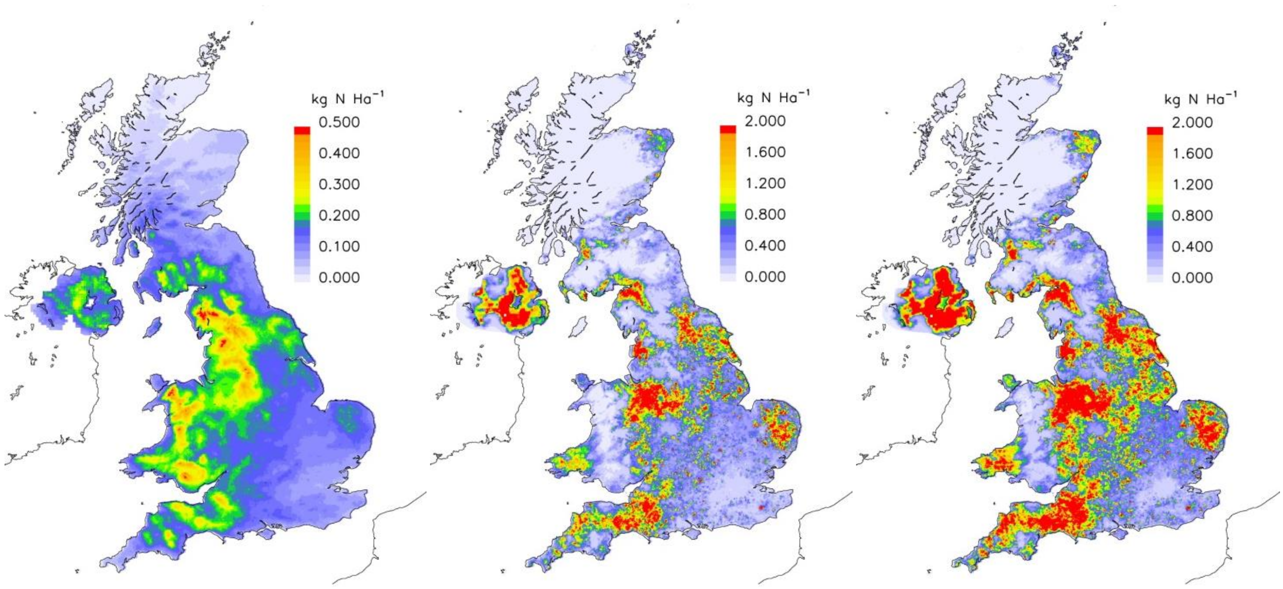


Figure 5: *Areas and amounts of total nitrogen deposition that is reduced from a 50% increase in forest cover (B2): Wet deposition (left); deposition to semi-natural non-forest land (centre); deposition to semi-natural forest (right)*

The two strategies described in this paper are in some ways quite similar – they both use the concept of planting trees to re-capture ammonia thereby protecting nearby semi-natural areas. Since both strategies have the ability to pinpoint where trees are planted they can be used to control where the ammonia deposits as a means to reduce inputs to semi-natural areas (e.g. downwind of animal housing units, storage facilities and spreading areas). However, while the two approaches are similar in their aims and N deposition reduction, they are quite different in their approach, application and amount of trees planted. Strategy A uses discreet blocks of woodland to capture ammonia around targeted ammonia hot-spots including livestock housing and manure storage, as well as directly placing livestock under the trees. Strategy B, while also targeting hot-spots, uses more of a blanket approach to distributing the trees in the landscape. Strategy A can be seen as a farming management switch to grazing livestock under trees and a sheltering of housing units with tree-belts. By contrast, Strategy B is more of a farm-forestry management technique that will not only capture ammonia to protect semi-natural areas, but also has the potential to provide timber products (e.g. for use as renewable fuels) and/or to improve carbon sequestration (increasing national carbon sinks) on a much greater scale than Strategy A. Both strategies augment the afforestation targets for the UK. Strategy B amounts to planting around 0.7 million hectares of trees for a 25% increase in forest, to 1.4 million hectares for a 50% increase in forest. Conversely for Strategy A much smaller areas of land are converted to trees. For example if the 26 million laying hens in the UK were converted to silvo-pastoral systems this would create around 10,000 ha of reforested land (stocking rate of 2500 birds/ha). 27,500 ha of new woodland could support the broiler population (110 million birds) in this way too (stocking rate of 4000 birds/ha).

One key point to be made is that both strategies are not actually reducing total emissions, but they are reducing on-farm emissions, and in both cases trees can be used as sacrificial land-use with the aim to buffer sensitive habitat areas in the landscape near agricultural areas.

Conclusions

Both strategies reduce nitrogen deposition to semi-natural areas, both target areas of high ammonia emissions, and both strategies lead to the reduction in wet deposition and the export of nitrogen out of the UK as more is captured at source by the trees. Scenario A_8 of Strategy A (the combination scenario) achieves around a 3.1 kt N-NH_x (2.2%) reduction in total nitrogen deposition across the UK, about the same as Strategy B of planting 25% more trees in the vicinity of ammonia hotspots. For Scenario A_8 wet deposition was reduced by 1.5 kt N-NH_x (2%) and export reduced by 3.2 kt N-NH_x (2%).Planting 50% more forest in Strategy B resulted in a 12 kt of N-NH_x (19.5% increase) being deposited to the planted areas. By increasing dry deposition to the planted areas it also gave an added value effect of reducing wet deposition by 3.7 kt N-NH_x (4.6% reduction) and reducing export from the UK of 8.3 kt (6.8% reduction).

In both strategies the higher cost of transferring arable land and grassland to forest land cannot be understated in terms of income, animal feed production, and crop harvests forgone as more trees are planted. Strategy A is certainly more suitable for the livestock industry to implement as it is more targeted and involves planting smaller discreet blocks of trees around sources. Strategy B has a more blanket approach to planting around the farm which could give far reaching implications for current food production as prime agricultural land is replaced by forestry. Managing nitrogen losses on the farm and improving the efficient use of nitrogen are the key components for overall reduction in NH_3 emissions. Planting trees around hot-spots of ammonia can reduce the potential impacts on nearby sensitive ecosystems and have added benefits of reducing long-range transport.

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Appendix

***Table A1:** Emission factor reduction for livestock types using two tree planting scenarios - livestock grazing under trees (45% reduction in NH_3), and sheltering housing units and manure stores with trees (20% reduction in NH_3).*

		Housing			Grazing			Storage and Spreading					
Livestock Type	**Management System**	**% Housing NH_3 Capture Efficiency**	**% time indoors**	**Housing Emission Factor**	**% Grazing NH_3 Capture Efficiency**	**% time outdoors**	**Grazing Emission Factor**	**% Storage NH_3 Capture Efficiency**	**% housing manure required for storage and spreading**	**Storage & spreading Emission Factor**	**Revised Total Emission Factor**	**Current 2008 total Emission Factor**	**% emission reduction**
Laying hens	*Control: full-time in housing, no free-range, no trees	0%	100%	0.155	0%	0%	0.000	0%	100%	0.109	0.264	0.264	**0%**
Laying hens	In housing upwind of tree belt, no ranging	20%	100%	0.124	0%	0%	0.000	0%	100%	0.109	0.233	0.264	**12%**
Laying hens	In housing upwind of tree belt + 25% ranging under trees	20%	75%	0.093	45%	25%**	0.019	0%	75%	0.081	0.194	0.264	**27%**
Laying hens	In housing under tree canopy (arks) + 25% ranging under trees	45%	75%	0.064	45%	25%	0.019	0%	75%	0.081	0.165	0.264	**38%**
Sows	Double the number of sows outdoors (currently 36%) + ranging under trees	0%	28%	0.750	45%	72%	1.072	0%	28%	1.022	2.844	5.242	**46%**

Other pigs >80-110 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	85%	2.473	45%	15%	0.203	0%	85%	2.182	4.857	5.310	**9%**
Other pigs >50-80 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	85%	2.131	45%	15%	0.165	0%	85%	1.884	4.180	4.580	**9%**
Other pigs >20-50 kg	Increase to 15% the herd outdoors (currently 0.01%) + ranging under trees	0%	85%	1.425	45%	15%	0.135	0%	85%	1.255	2.815	3.060	**8%**
Dairy cows & heifers	In housing upwind of tree belt, no ranging + slurry store with trees downwind	20%	46%	10.628	0%	54%	1.615	20%	46%	10.445	22.688	26.173	**13%**

Table A2: Full list of the 8 scenarios used for the FRAME model runs based on three woodland systems

SCENARIOS	**Livestock Category**	**EF reduction**	**Applicable% of UK flock/herd**
Scenario A1 POULTRY System 1: Housing with trees downwind, no free-range (↓20%)			
	Laying hens (Sys 1)	12%	50%
	Breeding birds (Sys 1)	8%	50%
	Broilers (Sys 1)	6%	50%
	Pullets (Sys 1)	8%	50%
	Turkeys (Sys 1)	11%	50%
	Other poultry (Sys 1)	8%	50%
Scenario **2 POULTRY** **System 2: Housing with trees downwind (↓20%) + free-range under trees (↓45%)**			
	Laying hens (Sys 2)	27%	37%*
Scenario **3 POULTRY – free ranging birds under trees, 70% houses sheltered, 30% in arks under trees** **System2: Housing with trees downwind (↓20%) + free-range under trees (↓45%)** **System3: Housing under trees (↓45%) + free-range under trees (↓45%)**			
	Laying hens (Sys 2)	27%	26%
	Laying hens (Sys 3)	38%	11%
	Laying hens (no reduction)	0%	63%
Scenario **4 POULTRY - broilers (50% houses sheltered, 10% forage under trees)** **System 1: 50% of broilers' houses sheltered with trees, no free-range (↓20%)** **System 2: Housing with trees downwind (↓20%), + free-range under trees (↓45%)**			
	Broilers (Sys 2)	23%	10%
	Broilers (Sys 1)	6%	50%
Scenario **5 POULTRY** **System1: Housing with trees downwind, no free-range (↓20%)** **System 2: Housing with trees downwind (↓20%), + free-range under trees (↓45%)**			

System3: Housing under trees (↓45%) + free-range under trees (↓45%)			
	Laying hens (Sys 1)	12%	63%
	Laying hens (Sys 2)	27%	26%
	Laying hens (Sys 3)	38%	11%
	Breeding birds (Sys 1)	8%	50%
	Broilers (Sys 1)	6%	50%
	Broilers (Sys 2)	23%	10%
	Pullets (Sys 1)	8%	50%
	Turkeys (Sys 1)	11%	50%
	Other poultry (Sys 1)	8%	50%
Scenario **6 Dairy+ Beef (20% of cattle houses and slurry stores sheltered)** **System 4: Housing with trees downwind (↓20%), + slurry store with trees downwind (↓20%)**			
	Dairy cows & heifers (Sys 4)	13%	20%
	Dairy heifers in calf, 2 years and over (Sys 4)	12%	20%
	Dairy heifers in calf, less than 2 years (Sys 4)	12%	20%
	Beef cows & heifers (Sys 4)	13%	20%
	Beef heifers in calf, 2 years and over (Sys 4)	13%	20%
	Beef heifers in calf, less than 2 years (Sys 4)	13%	20%
	Bulls >2 years (Sys 4)	13%	20%
	Bulls 1-2 years (Sys 4)	13%	20%
	Other cattle, over 2 years (Sys 4)	12%	20%
	Other cattle, 1-2 years (Sys 4)	13%	20%
	Other cattle, under 1year (Sys 4)	10%	20%
Scenario **PIGS (Double sows outdoor; 15% the rest both with foraging under trees)** **System 5: Free-range under trees (↓45%)**			

	Sows in pig & other sows (sows) (Sys 5)	46%	100%
	Other pigs, >80-110 kg (Sys 5)	9%	100%
	Other pigs, >50-80 kg (Sys 5)	9%	100%
	Other pigs, >20-50 kg (Sys 5)	8%	100%
COMBINATION (combination of SC5 Poultry, SC6 Cattle and SC7 Pigs)			
	Dairy cows & heifers (Sys 4)	13%	20%
	Dairy heifers in calf, 2 years and over (Sys 4)	12%	20%
	Dairy heifers in calf, less than 2 years (Sys 4)	12%	20%
	Beef cows & heifers (Sys 4)	13%	20%
	Beef heifers in calf, 2 years and over (Sys 4)	13%	20%
	Beef heifers in calf, less than 2 years (Sys 4)	13%	20%
	Bulls >2 years (Sys 4)	13%	20%
	Bulls 1-2 years (Sys 4)	13%	20%
	Other cattle, over 2 years (Sys 4)	12%	20%
	Other cattle, 1-2 years (Sys 4)	13%	20%
	Other cattle, under 1year (Sys 4)	10%	20%
	Sows in pig & other sows (sows) (Sys 5)	46%	100%
	Other pigs, >80-110 kg (Sys 5)	9%	100%
	Other pigs, >50-80 kg (Sys 5)	9%	100%
	Other pigs, >20-50 kg (Sys 5)	8%	100%
	Laying hens (Sys 1)	12%	63%
	Laying hens (Sys 2)	27%	26%
	Laying hens (Sys 3)	38%	11%
	Breeding birds (Sys 1)	8%	50%

	Broilers (Sys 1)	6%	50%
	Broilers (Sys 2)	23%	10%
	Broilers (remainder, no trees)	0%	40%
	Pullets (Sys 1)	8%	50%
	Turkeys (Sys 1)	11%	50%
	Other poultry (Sys 1)	8%	50%

**37% is the current proportion of free range laying hens in the UK*