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Research article

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

W.J. Bealey [a,*], A.J. Dore [a], U. Dragosits [a], S. Reis [a], D.S. Reay [b], M.A. Sutton [a]

[a] Centre for Ecology and Hydrology, Bush Estate, Penicuik EH26 0QB, United Kingdom
[b] School of Geosciences, University of Edinburgh, High School Yards, Edinburgh, EH8 9XP, United Kingdom

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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%).

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1. 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., 1998; Krupa, 2003; Pitcairn et al., 1998; Sheppard et al., 2008; Van den Berg et al., 2008; Wiedermann et al., 2009) and other

* Corresponding author.
E-mail address: bib@ceh.ac.uk (W.J. Bealey).

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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 et al. 2000; Nowak, 2000; Nowak 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.

2. 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 recapture 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.

2.1. Atmospheric dispersion modelling

The FRAME (Fine Resolution Atmospheric Multi-species Exchange) model (Singles et al., 1998; Fournier et al., 2004; Dore et al., 2007, 2012; Vieno et al., 2010) 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 1 km grid resolution has been used to assed critical level exceedance of ammonia over the UK's Natura 2000 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 Fig. 1.

2.2. 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). We assessed three farm

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