QUANTIFYING OZONE IMPACTS ON THREE ECOSYSTEM SERVICES IN THE UK

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Ozone impacts have been previously quantified for some provisioning services such as timber and crop production at the European scale (Harmens and Mills, 2012, Mills and Harmens, 2011) and crop production at the UK scale (Mills et al., 2011). However, valuation of ozone impacts has not been conducted as marginal costs (i.e. the marginal cost of a change from one pollutant level to another) for any services in the UK using spatially explicit calculations.

Here we report on progress to value the marginal cost of ozone pollution for three ecosystem services:

- Livestock production (provisioning)
- Carbon sequestration in grasslands and woodland (regulating)
- Biodiversity appreciation (cultural)

Effects were compared over two time periods: Historical (1987-2007) and Future projections (2007-2020). Dose-response relationships were derived from Defra ozone-umbrella research consortium experiments, combined with other literature where appropriate. For example, using data combined from open-top chamber, solardome and field release experiments, a relationship was established between increasing 24h mean ozone concentration and decreasing forage quality for conservation-grade pasture. We were able to use this to value effects on livestock density and growth rate. Progress has also been made with valuing effects on carbon sequestration in the living biomass of grasslands and trees, and with developing simple dose-response relationships from spatial data of ozone and biodiversity indicators taking into account other modifiers. This study has resulted in significant progress towards providing spatial valuation of ozone pollution impacts on ecosystem services in the UK.

Policy relevance

- In many environmental policy areas, there is increasing focus on quantifying the services that ecosystems provide, including valuation wherever possible.

- In this study, the concept of marginal costs is applied to ozone effects allowing cost comparisons for effects of different pollutants and other drivers of change such as land-use and management practices.

- Progress has been made with valuing ozone effects on pasture quantity and quality, C sequestration in the living biomass of trees and grassland, and with developing relationships of relevance to appreciation of biodiversity.

THE EFFECTS OF OZONE ON BIOMASS, NODULATION AND NITROGENASE ACTIVITY OF CLOVER CULTIVARS

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At present, background levels of tropospheric ozone in the Northern hemisphere are high enough to damage sensitive crops and semi-natural vegetation. The legume-rhizobia symbiosis, contained within specialised organs called root nodules, is thought to add at least 30 Tg N to agricultural soils per year (Herridge *et al.* 2008). Clovers (*Trifolium spp.*) are important components of temperate pasture, improving the protein content, nutritional value and uptake of forage, as well as providing ancillary benefits to nutrient retention and utilisation, soil structure and long term soil fertility. In this paper, the effects of ozone on the biomass and nodulation of currently-used cultivars of white clover (Crusader) and red clover (Merviot) were assessed using the solardome system at CEH Bangor. The effect of ozone on system nitrogenase activity in Crusader was also determined. Ozone caused systemic reductions in root and total biomass and reductions in the number of nodules in both cultivars. Nodule size in Crusader was also reduced, and nitrogenase activity showed consistent declines in high ozone (an episodic regime with a 24h mean of 66 ppb). Reduced allocation of assimilate to the root system is suggested as the cause for the reduction in nodule growth and nitrogenase activity. The possible implications for the sustainability of pasture are discussed in relation to current and predicted future ozone concentrations.
Herridge, D.F., Peoples, M.B. & Boddey, R.M. (2008). Global inputs of biological fixation in agricultural systems. *Plant Soil*, **311**: 1-18.

Defra policy relevance:

- Clovers, a critically important component of temperate pasture, are one of the most ozone-sensitive genera.
- Results show that not only does ozone reduce biomass; it also reduces the nitrogen fixation capacity of clover in recommended cultivars.
- Such effects have the potential to reduce the sustainability of pasture and could also lead to increased fertiliser use by producers.

BELOW GROUND EFFECTS OF OZONE IN MEADOWS

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Among meadow species, especially legumes appear to be sensitive to elevated O_3 concentrations in terms of biomass loss. This may mainly be due to O_3-related reduction in C allocation to roots and the N_2-fixing symbiotic bacteria. However, few experiments have focused on below ground effects of O_3 in meadow ecosystems. We exposed mesocosms (3 forb + 2 grass + 2 leguminous species), and mono-cultured legume (*Lathyrus pratensis*) and grass (*Agrostis capillaris*) to realistic O_3 levels (40-50 ppb), alone and combined with elevated CO_2 (+100 ppm), in open-top chambers during 2002-2004. Here we review main results on soil microbial community structure and size (analysed by the PLFA method), C and N cycling including greenhouse gas fluxes, and nutrient concentrations.

O_3 reduced the total PLFA biomass in the mesocosm soil and in the bulk soil of *L. pratensis* (5% and 25%, respectively; $p<0.05$), but not beneath *A. capillaris*. O_3 also reduced the fungal:bacteria PLFA biomass ratio, NH_4^+-N and mineral N concentrations, N_2O and CO_2 emissions, and CH_4 fluxes (at $p<0.05$ or $p<0.1$) in the mesocosm soil. The pot experiment suggested that the changes in microbial community structure and size under elevated O_3 were associated especially to changes in soil C:N ratio and concentration of readily available P. Results on both mesocosm and *A. capillaris* soil also suggested O_3-related changes in the function of sulphate reducing bacteria. Overall, the results on *L. pratensis* point to interactions and multi-trophic feedbacks between elevated O_3, plant, parasitic rust fungi and soil P concentration, accompanied by a shift in N balance in favour of plants rather than soil micro-organisms. The effects of elevated CO_2 were minor compared to those of O_3 alone.

Research highlights and implications

• Ambient O_3 levels can induce alterations in soil microbial community and nutrient and C cycling including N_2O, CO_2 and CH_4 fluxes.

• At the ecosystem level, the alterations may be mediated especially by O_3 effects on legumes.

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- Manninen et al. 2010. Plant and soil microbial biomasses in *Agrostis capillaris* and *Lathyrus pratensis* monocultures exposed to elevated O_3 and CO_2 for three growing seasons. Soil Biol. Biochem. 42, 1967-1975.

DOES RISING TROPOSPHERIC OZONE ALTER THE FLOWERING BEHAVIOURS OF UK UPLAND GRASSLAND SPECIES?

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Tropospheric ozone levels are of concern in the UK, as, not only are they regularly exceeding critical levels, but background levels are gradually increasing as a result of global-scale effects. Plant species are known to have variable sensitivity to ozone, and these varying responses could cause shifts in community interactions and ultimately composition, with implications on biodiversity.

This presentation reports the findings from a long-term field-based ozone fumigation study, based in a mesotrophic grassland site at High Keenley Fell, situated near Allendale, Northumberland (NY 7922 5586), and managed under a Defra Higher Level Stewardship Scheme aimed at restoring hay meadow floral diversity. Operating since 2007, the study site had three replicate transects, within which there were three ozone treatments: ambient (~30 ppb in 2011); ambient + a targeted 10 ppb; and ambient + a targeted 25 ppb. Each transect used an independent ozone generator, and these released ozone when wind direction was SW (180°-270°). Fifteen species selected for their restoration value (6 grasses, 7 forbs and 2 legumes) were assessed via periodic counts of flowering heads within 1 m^2 plots at each treatment level between June and August for each year from 2010-2012, to establish peak flowering density for each species in each year.
Increasing background ozone concentrations led to responses of both positive (e.g. *Dactylis glomerata*, a grass of relative unimportance in grassland restoration, which benefitted most from a +10 ppb increase), and negative natures (e.g. *Ranunculus acris*, a forb of interest in restoration terms, which saw a sharp decline in flower density at both background level increases) in terms of flowering density. Additionally, some species showed neither positive nor negative responses to increased ozone, such as *Anthoxanthum odoratum* (a valuable grass species in conservation terms), which indicates that some species may be resilient to increasing background ozone.

Defra policy relevance:

- Grassland species can respond positively, negatively, or be resilient to slight increases in ozone concentration. An increase of 10 ppb is possible within this century, and from the results of this study there is a real risk of major shifts in grassland species composition, which would hinder schemes aimed at restoring forb-rich grasslands.

IMPACTS OF OZONE POLLUTION ON PLANT-POLLINATOR INTERACTIONS-POTENTIAL INFLUENCES ON BUMBLEBEE FORAGING

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Aim: to investigate the influence of ozone pollution on the volume and composition of nectar produced by flowers and determine the consequences for bumblebee foraging.

Dwarf broad bean plants were subject to one of four treatments; sustained exposure to clean air, sustained exposure to elevated levels of ozone, short-term transfer at flowering from ozone-enrichment to clean air and vice versa.

Nectar and pollen were sampled and analysed for carbohydrates and amino acids by HPLC. Plants were subject to destructive harvest and dry matter accumulation and partitioning assessed. Bee behavioural studies were conducted under carefully controlled conditions.

There were no significant impacts of the ozone exposure on the broadbean plants per se: no visible symptoms, no effects on dry weight and no effects on resource partitioning between root and shoot. However, there were dramatic effects of ozone on nectar quality and composition, with amino acids and carbohydrates withheld from nectar in ozone treated plants. Interestingly, where plants were grown under ozone then moved into clean air, both carbohydrate and amino acid composition of nectar was substantially enhanced, along with the volume of nectar produced.

Bumblebees have a target intake of both carbohydrates and amino acids and the manner in which these influence bumblebee foraging will be known by the time of the CAPER meeting. Early results of this project suggest that bumblebee foraging may prove more sensitive to ozone than direct effects on the plant per se.

SOIL MICROBIAL COMMUNITY OF MG3b MESOCOSMS EXPOSED TO ELEVATED OZONE FOR 9 YEARS

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Elevated tropospheric ozone may result in plant-mediated impacts on soil properties and soil microbial communities. This may occur via changes in plant community composition, altered plant carbon partitioning and changes to litter quality and quantity. Several previous studies report increased lignification of ozone-exposed foliage. The suggestion being that rising levels of ozone pollution may enhance litter recalcitrance and slow decomposition and carbon release from upland soils – a hypothesis as yet untested experimentally in an established grassland system and one that may profoundly influence carbon turnover in these habitats.

Mesocosms containing the rare *Anthoxanthum odoratum-Geranium sylvaticum*, *Briza media* sub-community (MG3b) were exposed to two ozone regimes over nine consecutive years in open-top chambers (OTCs). The ozone regimes simulated current (~30 ppb) and projected future ozone concentrations (~50 ppb) in rural areas across Europe. Elevated ozone exposure reduced the above-ground community productivity and changed the relative abundance of the component plant species and preliminary results suggest that 9 years' ozone exposure may have changed key soil properties such as organic carbon content. We report initial analysis of soil properties and bacterial and fungal communities of the MG3b mesocosms using Denaturing Gradient Gel Electrophoresis (DGGE).

LONG-TERM ELEVATED BACKGROUND TROPOSPHERIC OZONE ALTERS PLANT SPECIES DYNAMICS IN SIMULATED UPLAND MESOTROPHIC GRASSLAND OF HIGH CONSERVATION VALUE

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Background upland ozone climates in the UK and throughout Europe are predicted to rise significantly during this century, potentially negating management practices designed to promote (semi-)natural grassland ecosystem services such as productivity and biodiversity. Few studies to date have investigated the species dynamics and productivity of complex grassland plant communities over many consecutive growing seasons. Mesocosms containing the rare *Anthoxanthum odoratum-Geranium sylvaticum*, *Briza media* sub-community (MG3b) were exposed to two ozone regimes over nine consecutive years in open-top chambers (OTCs). The ozone regimes simulated current (~30 ppb) and projected future ozone concentrations (~50 ppb) in rural areas across Europe. Total productivity varied with time, and was reduced by elevated ozone treatment ($P \leq 0.005$). The relative abundance of the component species also showed inter-annual variation, and consistent negative effects of elevated ozone were observed on the biomass of the dominant grass *Briza media* ($P \leq 0.005$), and the dominant legume *Lotus corniculatus* ($P \leq 0.005$). Elevated ozone reduced the frequency of *Rhinanthus minor*, an ecologically important hemi-parasite, which may further influence the plant community structure and reduce the success of hay-meadow restoration management schemes. Regression analysis of cumulative sward biomass with cumulative ozone exposure revealed that the elevated ozone scenario did not match the more linear response observed in the 'present-day' scenario; an effect only apparent after several years of ozone exposure. Our results underscore the importance of long-running studies on established complex species-mixtures to better understand how grassland communities are likely to respond to increasing background ozone in the future.

ANALYSIS OF THE GENETICS UNDERLYING OZONE AND DROUGHT TOLERANCE IN WHEAT

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The goal of this research programme is to ultimately identify the genetic basis for tolerance to ozone and/or drought stress in wheat, and ultimately assist wheat breeders in the production of high yielding lines exhibiting enhanced tolerance to multiple environmental stresses. Such plant material would be better positioned to secure food production in a changing climate.

The advent of molecular marker technologies coupled with the analysis of quantitative trait loci (QTLs), and association genetics, has allowed regions of the wheat genome that regulate yield and other important agronomic traits to be identified. The latest stage in the ongoing programme at Newcastle has been the production of near isogenic lines (NILs) which focus on 12 regions of the bread wheat genome where major QTL clusters for yield, its components, phenology, leaf dimension and antioxidative capacity have been located using a much-studied Chinese Spring (CS) x SQ1 mapped population.

To confirm whether the targeted QTL region had been successfully retained or not, and to compare consistency in QTL expression between different (stress) environments, productivity traits (kernel weight per plant, kernel number per plant, mass of 1000 grains, biomass per plant and harvest index) were measured in a set of 58 NILs, comprising at least two QTL++ and QTL-- plants (with ***CS*** or ***SQ1 alleles*** in an ***SQ1 background, respectively)*** for 11 marker loci. Trials were conducted on these plants exploring yield under either drought (about 50% soil water capacity) or ozone-induced oxidative stress (NFA plus 50 ppb 8 h d^{-1}). Both, drought and ozone stress significantly depressed productivity (25% and 15%, respectively, across all traits). Interestingly, a QTL on chromosome 5DL (wmc97), and two on chromosome 6B (gs1-sust and wmc397), were shown to influence productivity exclusively under drought, while a locus on 4BL (dupw43) was ozone-specific. Three loci: gwm2 on 3AS, gwm219 on 6BL and cfd49 on 6DS, were associated with yield related-traits under both drought and ozone stress. These newly-identified loci are under further dissection but could prove an important step forward in breeding future wheat genotypes for combined tolerance to drought and ozone stress.

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AIR POLLUTION EFFECTS RESEARCH IN A CHANGING WORLD

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In the forty years since the first CAPER meeting, there have been dramatic changes in exposure to air pollution in the UK, which have been reflected in remarkable changes in the emphasis of the research that we discuss every year. Perhaps more importantly, over these forty years, forces such as globalisation, economic development, and population growth have led to dramatic changes in exposure to air pollution in different regions of the planet. Over the same period, the threat of global warming has become much more evident, and there is an increasingly urgent need to reduce emissions of CO_2, and other short-term and long-term climate forcers, alongside those of air pollutants.

Looking forward, what will the future bring and what implications does this have for our future research priorities on air pollution impacts on ecosystems? What further changes in the air pollution climate of the UK, Europe and the planet can we expect in the next 20 years? Are there new pollutants or sources that we need to consider? What will the key policy drivers be nationally and internationally over this period? What are the key synergies between climate change and air pollution in terms of both ecosystem impacts and policy? Do we have the necessary mechanistic understanding to predict the interactive effects of pollution exposure, climate change and trace gas fluxes? Should and could we be doing more to support researchers in regions of the world where air pollution impacts are now greatest? Do we have the right mix of facilities and expertise in the UK or CAPER research community to address key future research priorities? Are we communicating the importance of our science effectively enough to policy makers and to the wider public?

This talk aims to provide an overview of some of these questions and, most importantly, to provoke a lively discussion and debate.

IMPACT OF NITROGEN DEPOSITION ON UK BIODIVERSITY

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A wealth of evidence demonstrates that Nitrogen deposition is a driver of change in plant species richness in UK semi-natural habitats. Experiments show that in many habitats addition of nitrogen (often at high doses and for short periods of time) leads to the loss of species. Time-series studies show that many habitats have lost species over time and become more homogenous in composition. Targeted gradient studies and untargeted ecological surveillance data show that there are landscape-scale correlations between greater nitrogen deposition and lower plant species richness. Our aim in this project is to up-scale, hind-cast and forecast nitrogen deposition impacts on UK plant biodiversity. We use relationships identified in targeted gradient studies as response functions which we apply to data on 1) distribution of NVC habitat types, 2) contemporary nitrogen deposition, 3) historical nitrogen deposition and 4) possible future nitrogen deposition. Combining these datasets we first model N deposition impact on contemporary UK habitats, inferring considerably lower species richness in areas of high N deposition in the south and west of the UK. The impacts on different habitats are a function of their sensitivity to nitrogen and their distribution relative to areas of high deposition. Using data on historical N deposition we show that these impacts developed slowly in the early part of the twentieth century accelerating through the latter part of the 20th century and early 21st century. Initial studies of possible future deposition scenarios suggest impacts intensifying and extensifying across Great Britain. Results are valuable for communicating the threat posed by nitrogen to policy makers and as a tool for assessing the consequences of alternative policy options.

- This paper has DEFRA-policy relevance by illustrating the potential scale of N impacts on biodiversity and providing a mechanism for evaluating the impacts of future deposition scenarios.

SIMULATED N DEPOSITION EFFECTS ON SOIL FAUNA FROM A SEMIARID MEDITERRANEAN ECOSYSTEM IN CENTRAL SPAIN

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Nitrogen deposition is currently recognized as a major threat to terrestrial ecosystems worldwide, including those from the semiarid Mediterranean regions. Recent studies have demonstrated detrimental effects of N deposition on local plant communities and soil C accumulation in these ecosystems. However, little attention has been paid to the effects of increased N deposition on soil fauna. In this study, we simulated a gradient of N deposition (0, 10, 20 and 50 kg N ha^{-1} yr^{-1} + 6.4 kg N ha^{-1} yr^{-1} ambient deposition) in a semiarid Mediterranean shrubland from central Spain. In autumn 2011 (after 4 years of experimental duration), soil cores (0-10 cm depth) were taken from each replicated treatment (N = 6). Soil fauna was then extracted with Berlesse funnels and individuals identified to the order level. Acari (45.54%) and Colembolla (44.00%) were the most represented taxonomical groups and their abundance was negatively related to soil pH. Soil pH was, in turn, positively related to soil fauna diversity. Simulated N deposition had an impact on the total number of individuals in soil as well as on Colembolla and Pauropoda abundance. Colembolla abundance increased with N loads up to 20 kg N ha^{-1} yr^{-1} and then decreased. This response was mainly attributed to soil acidification (between 0 and 20 kg N ha^{-1} yr^{-1}) and increased soil NH_4^+ toxicity (between 20 and 50 kg N ha^{-1} yr^{-1}). Pauropoda were significantly favoured by additions of 50 kg N ha^{-1} yr^{-1} and it was the only soil taxonomical group whose abundance was exclusively related to simulated N deposition, suggesting its potential as a bioindicator group. In conclusion, soil fauna communities from semiarid Mediterranean ecosystems in central Spain seem to be greatly influenced by soil chemical properties (mainly soil pH) but are also susceptible to be altered by increased N deposition. The main drivers of change under increased N deposition scenarios seem to be soil acidification and increased NH_4^+ toxicity in soils where NO_3^- is usually the dominant mineral N form.

CHANGES IN LEAF COLOUR OF THE CARNIVOROUS PLANT *DROSERA ROTUNDIFOLIA* DUE TO NITROGEN DEPOSITION: A NOVEL INDICATOR OF ABOVE-GROUND INTERACTIONS AND N DEPOSITION?

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Carnivorous plants attract, capture and digest animal prey assimilating the nutrients into their tissues. Carnivorous plants tend to grow in high light, low nutrient systems such as ombrotrophic bogs. As such, they might be particularly threatened by N deposition. However, they might also be sensitive indicators because even low levels of N deposition will result in a large relative increase in root N availability. Aspects of carnivorous plant morphology (e.g. pitcher plant shape) and physiology (e.g. 'fly trap' stickieness) have been shown to respond to N deposition and availability. These responses indicate a reduced investment in carnivory when root N availability is increased and so prey derived N is less valuable to the plants. The red colour of many carnivorous plant species, particularly those in the genus *Drosera* is thought to function as a prey attraction mechanism, as colour is in flowers. However, there is little evidence to support this role.

We measured trap/leaf colour of the carnivorous plant *Drosera rotundifolia* growing in ombrotrophic bogs across a European N deposition gradient. We wanted to determine whether leaf colour changed from red to green when N deposition increased, as would be predicted if colour is a prey attraction mechanism. However, we also investigated an alternative hypothesis that the red colour is for photoprotection and so might respond to increasing shade intensity when N deposition increases.

Implications and research highlights

We found clear evidence that the red colour of *D. rotundifolia* leaves is for photoprotection and not for prey attraction. We found a strong relationship between N deposition and leaf/trap colour, and between canopy shading and leaf/trap colour. We suggest that *D. rotundifolia* leaf/trap colour might be a novel bioindicator of N deposition. We also suggest that the changes in trap colour seen across the European N deposition gradient indicate increased intensity of above-ground interactions in response to N deposition.

TOO MUCH OF A GOOD THING: ENVIRONMENTAL IMPACTS OF INCREASING ATMOSPHERIC NITROGEN DEPOSITION ON PEATLANDS

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Increasing atmospheric nitrogen (N) deposition is a major threat to natural ecosystems. Since N is a macronutrient for plants, increased atmospheric supply of N is expected to impact the structure and function particularly of those ecosystems that are, by their nature, nutrient-poor such as peatlands. In this talk, I will review some of the environmental impacts associated with increasing N supply in *Sphagnum*-dominated peatlands. I will first focus on the effects at “organism level” with reference to plant and soil microbial community. Then, I will discuss some major impacts at “community level”, with particular attention to the process of decomposition of organic matter and greenhouse gas emission. Finally, the synergic impacts of increasing N deposition and climate warming will be highlighted.

ATMOSPHERIC NITROGEN DEPOSITION IN A HOLM OAK FOREST IN CENTRAL SPAIN

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Emissions of atmospheric nitrogen (N) compounds in Spain have continued increasing since 1990. Emissions of NH_3 increased 13.3% for the period 1990-2009, while NOx emissions increased until 2007 and afterwards decreased resulting in 17% lower emissions in 2009 than in 1990. Despite this increasing trend, little information is available on N deposition and effects that could be occurring in Spanish natural ecosystems. Total annual estimates of N deposition loads in eastern Spain are 10-30 kg N ha^{-1} yr^{-1} (Sanz et al., 2002; Avila et al., 2010). These values are lower than values recorded in central Europe, but some evidences indicate that N enrichment is already occurring in some ecosystems, such as the increasing trend in relative richness of nitrophilous species in herbaria (Ariño et al., 2010) and the increasing nitrate content in rivers in NE Spain (Ávila & Rodá, 2011). Interestingly, dry deposition can represent about 40-75% of total N atmospheric deposition in Mediterranean ecosystems (Rodá et al., 2002; Sanz et al., 2002). However, characterizing dry deposition is still challenging since no standard method is available.
A new study has been developed to evaluate the contributions of dry and wet atmospheric N deposition and their temporal variations in a Holm oak forest in Central Spain. The study was performed in Tres Cantos, at 20 km from Madrid city. Main air pollutant concentrations (NO_2, NH_3, HNO_3 and O_3) were measured every two-week using passive samplers in an open area and inside the forest for two years (2011-2012). Additionally, O_3, NOx and particulate matter were continuously monitored using automatic analyzers at an experimental station nearby. Wet and dry N deposition was measured comparing different methods. Bulk and throughfall samples were collected weekly for the same period using Nilu precipitation collectors with 20 cm of diameter. Also bulk and throughfall samples were collected seasonally using ion exchange resin columns. Dry deposition was estimated seasonally by means of rinsing techniques of both natural and lyophilized branches. Wet deposition estimations were compared with values obtained with a wet-only deposition sampler. Preliminary results will be presented showing that air pollutant concentrations inside the forest were always lower than in the open area. Concentrations of O_3, HNO_3 and NH_3 were higher in summer while NO_2 levels peaked in winter. Bulk N deposition was very low the first year, 2.33 kg N ha^{-1} (58% as N-NO_3 and 42% as N-NH_4), probably due to the exceptionally dry winter.

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DEVELOPING SUSTAINABLE FARMING SYSTEMS BY VALUING ECOSYSTEM SERVICES

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Farmers tend to view sustainability as staying in business, i.e. making a profit, and for good reason. However, they have been under pressure for many years now to meet environmental targets. How can farmers meet their primary business need and the, sometimes legal, demands for environmental protection in terms of air and water quality and biodiversity?

A method known as Total Factor Productivity is presented and applied for optimising the sustainability of agricultural production systems in terms of both economics and the environment. Components of the agricultural production chain are analysed using environmental life-cycle assessment (LCA) and a financial value attributed to the resources consumed and burden imposed on the environment by agriculture, as well as the products. The sum of the outputs is weighed against the inputs and the system considered sustainable if the value of the outputs exceeds those of the inputs, i.e. the ratio Outputs:Inputs >1. If this ratio is plotted against the sum of inputs for a range of levels of inputs (effectively different farming systems) then in many cases an optimum level of sustainability is located at the maximum of the curve.

Data for a number of different farming systems – arable and livestock - were taken from standard economic almanacs and from published LCA reports on the extent of consumption and environmental burdens resulting from farming in the UK. Land-use is valued using the concept of ecosystem services. The analysis suggests that some of the agricultural systems examined are sustainable at rates of production close to current levels practiced in the UK; others struggle to meet this 'sustainability' criteria under any system. Productivity per unit area of land and greenhouse gas emission (subsuming primary energy consumption) is the most important pressures on the sustainability of farming.

In the context of the 'Land Sharing vs Land Sparing' debate, the analysis shows that extensification requires more land to produce the same amount of food. The lost value of non-food ecosystem services provided by that land is greater than that which can be provided by the land now under extensive farming; the loss is large in comparison to the benefit of a reduction in emissions of nutrients and pesticides. With food production once again being a priority, measures to ensure that as little extra land is brought into production as possible or that allow marginal land to revert to nature would seem to be well aimed, even if this requires more intensive use of productive areas. Some potential 'win-wins' are described.

Reference: Glendining, M.J., Dailey, A.G., Williams, A.G., van Evert, F.K., Goulding K.W.T. and Whitmore, A.P. (2009) Is it possible to increase the sustainability of arable and ruminant agriculture by reducing inputs? *Agricultural Systems* **99**: 117-125.

OZONE AND NITROGEN INTERACTIONS IN BIRCH TREES

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Birch trees (*Betula pendula*) were exposed to factorial combinations of seven ozone and four nitrogen regimes for five months in solardomes at CEH Bangor. The ozone regime was designed to investigate the benefits of changes in air quality policy that are anticipated to reduce both background and peak ozone concentrations, but with a larger reduction for the peaks. The range of ozone exposure treatments was from 31.5 ppb to 64.3 ppb (24h mean) and the nitrogen treatments were applied weekly as ammonium nitrate to give treatments equating to 10, 30, 50 and 70 kg ha^{-1} yr^{-1}. Measurements were made at both the leaf level and at whole-tree level to investigate whether: nitrogen modifies the response to ozone; whether nitrogen and/or ozone treatment alter the DO_3SE parameterisations for birch; whether fluxes of ozone and carbon become uncoupled; and to investigate whether whole-tree alterations in fluxes are a consequence of individual leaf physiological responses or via alterations in tree biomass.

There was a reduction in tree growth with increasing ozone exposure, coupled with a reduction in the number of leaves, but no significant effect of nitrogen on tree growth and no significant interaction between ozone and nitrogen on tree growth was detected in the first year of study. At the leaf level there was increasing stomatal conductance with increasing nitrogen treatment. When this effect was incorporated into the DO_3SE model by using separate parameterisations for the different nitrogen treatments, there was an improved fit of the relationship between ozone flux and tree growth compared to using a single parameterisation for all four nitrogen treatments.

For young leaves there was no effect of ozone or nitrogen on photosynthesis at saturating light levels (A_{sat}), but there were slight reductions in both photosynthesis and stomatal conductance with increasing ozone for older leaves. These corresponded with reductions in both V_{cmax} and J_{max} with increasing ozone in older leaves, which may indicate that either ozone damage is slow and based on cumulative exposure, or that re-allocation of plant resources occurs to repair younger leaves at the expense of older leaves. Effects of ozone on individual leaves coupled with decreased leaf number in elevated ozone treatments at the end of the exposure indicates that whole tree net ecosystem exchange of carbon would be reduced with increasing ozone treatment, and this was confirmed by measurements of whole tree carbon fluxes using a custom built chamber.

These effects of nitrogen and ozone observed at the leaf level during the course of the exposure indicate that growth and tree fitness may be affected over a timescale of longer than one season. The trees have continued to receive nitrogen treatments throughout the winter and will be exposed to a second season of ozone treatments in 2013.

Policy implications

- Ozone pollution has been shown to decrease growth (and therefore carbon sequestration) of birch trees
- Nitrogen treatment affects stomatal fluxes of birch and therefore nitrogen deposition should be accounted for when calculating ozone fluxes to inform assessments of vegetation at risk of ozone pollution
- The cumulative effects of these two stresses require further study over several years as leaf-level measurements indicate that additional effects and interactions may occur over longer timescales

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UK EUTROPHYING AND ACIDIFYING ATMOSPHERIC POLLUTANTS MONITORING (UKEAP): RESULTS AND FUTURE OUTLOOK

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UKEAP consists of the operation of two UK EMEP supersites for detailed process measurements and four monitoring networks measuring atmospheric acidifying and eutrophying species in the rural environment: National Ammonia Monitoring Network (NAMN): monthly ammonia concentrations in air at 85 sites, operational since 1996; Acid Gas and Aerosol Network (AGANet): monthly gas phase SO_2, HNO_3, HCl; major particulate phase inorganic anions and cations at 30 sites, operational since 1999; Precipitation Network (Precip-Net): fortnightly inorganic anion and cation concentrations in precipitation at 39 sites, operational since 1985; NO_2 diffusion tube Network (NO_2-Net): four-weekly NO_2 concentrations in air at 24 sites, operational since 1994. The UKEAP measurements underpin UK pollutant deposition and critical load/level mapping and the capability to understand changes in rural air quality in the UK over time. The measurements contribute to validation of atmospheric models. This paper summarises the results from NAMN and AGANet since the inception of the networks and discusses potential future drivers for rural air quality in the UK and how they may be monitored.

ON-SITE HABITAT MANAGEMENT TO REDUCE ATMOSPHERIC NITROGEN IMPACTS ON TERRESTRIAL HABITATS

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The deposition of reactive nitrogen (N) has more than doubled over the last one hundred years as a result of agricultural intensification and increased burning of fossil fuels by traffic and industry. In the UK only small declines in N deposition are predicted in the next ten years. Atmospheric deposition of reactive N has the potential to enrich the N content of soils, resulting in increased plant growth and hence competition for light and other resources, and to acidify soils reducing the number of species that can tolerate these conditions and coexist. The potential loss of biodiversity as a result of N deposition has important implications for both environmental and agricultural policy. Given the widespread impacts on habitats in the UK it is essential to understand how habitat management measures could reduce nitrogen deposition impacts and promote recovery.

This talk will report initial findings of a project conducted for Countryside Council for Wales, Natural England, Scottish Natural Heritage, Department for Environment Northern Ireland and the Joint Nature Conservation Committee with the aim of:

- Reviewing the effectiveness of 'on-site' land management methods to reduce nitrogen deposition impacts on sensitive habitats and species or to aid recovery;
- Assessing what effect current management practice, used by the conservation bodies, has on habitat response to nitrogen deposition;
- Considering how measures may be affected by climate change or management in response to climate change, in the near-term, or may affect habitat vulnerability to climate change;
- Recommending realistic and practical management measures for different habitat types which could be used to reduce nitrogen impacts or speed recover.

Management recommendations were made for woodlands, acid grasslands, calcareous grasslands, dwarf shrub heath bogs and coastal dunes. Initial recommendations were discussed with habitat specialists to ensure they were practical and didn't conflict with other conservation priorities.

CHALLENGES IN DETECTING THE ECOSYSTEM IMPACTS OF POLLUTANTS DEPOSITION

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One of the major challenges in detecting the ecosystem impacts of pollutants deposition is discriminating these effects in the presence of partial signals attributable to other global change phenomena such as land use and climate change. Large scale survey data are also used as a primary source for such studies but it is in these kinds of datasets that such problems can be particularly acute since other potential drivers can operate in ways that are by definition beyond the control of the observer. Thus high realism comes at a cost. Other analytical problems can include multiple random effects, missing data and different data types. In addition explanatory variables may exhibit a high degree of intercorrelation. We show how path analysis in a Bayesian framework can help address all these problems. We use examples of the effects of sulphur and nitrogen deposition on a range of terrestrial ecosystems in Britain.

THE GLOBAL NITROGEN CYCLE IN THE 21ST CENTURY

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Global nitrogen fixation contributes 413 Tg of reactive nitrogen (Nr) to terrestrial and marine ecosystems annually of which anthropogenic activities are responsible for half, 210 Tg-N. The majority of the transformations of anthropogenic Nr are on land (240 Tg-N yr^{-1}) within soils and vegetation where reduced Nr contributes most of the input through the use of fertilizer nitrogen in agriculture. Leakages from the use of fertilizer Nr contribute to nitrate (NO_3^-) in drainage waters from agricultural land and emissions of trace Nr compounds to the atmosphere. Emissions, mainly of ammonia (NH_3) from land together with combustion related emissions of nitrogen oxides (NOx) contribute 100 Tg-N yr^{-1} to the atmosphere, which are transported between countries and processed within the atmosphere, generating secondary pollutants including ozone and other photochemical oxidants and aerosols, especially ammonium nitrate (NH_4NO_3) and ammonium sulphate$(NH_4)_2SO_4$. Leaching and riverine transport of NO_3^- contribute 40-70 Tg-N yr^{-1} to coastal waters and the open ocean, which together with the 30 Tg input to oceans from atmospheric deposition combine with marine biological nitrogen fixation (140 Tg-N yr^{-1}), to double the ocean processing of Nr. Some of the marine Nr is buried in sediments, the remainder being denitrified back to the atmosphere as N_2 or N_2O. The marine processing is of a similar magnitude to that in terrestrial soils and vegetation, but has a larger fraction of natural origin.

The lifetime of Nr in the atmosphere with the exception of N_2O is only a few weeks, while in terrestrial ecosystems, with the exception of peatlands (where it can be 102 -103 years), the lifetime is a few decades. In the ocean, the lifetime of Nr is less well known but seems to be longer than in terrestrial ecosystems and may represent an important long term source of N_2O which will respond very slowly to control measures on the sources of Nr from which it is produced.

SPHAGNUM IN THE SOUTHERN PENNINES

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The blanket bogs of the Southern Pennines are the most degraded peatlands in the UK. A history of industrial pollution, poor land management and wildfire has devastated these upland ecosystems. Sensitive species were all but eradicated from these areas, and in the most severe cases, all vegetation was lost leaving large areas of bare and actively eroding peat. Over the last 50 years or so, conditions have steadily improved: reduced industrial activity, tighter emission regulations and environmental stewardship subsidies are all significant factors.

Sphagnum is a keystone species, providing the very fabric and functioning of these blanket bogs. Its susceptibility to pollution led to widespread decline over a landscape it once dominated. Amid the improving environmental conditions of recent decades, there has been a notable increase in both *Sphagnum* cover and diversity.

This work aims to characterise the differences between conditions of the degraded blanket peats of the Southern Pennines and those of more pristine mires from across the UK, identifying those biogeochemical factors that influence the vegetation, and integrating this into current and on-going restoration works.

UNDERSTANDING MODELLED AIR QUALITY RISK ASSESSMENTS AND SITE SPECIFIC RESPONSES TO AMMONIA POLLUTION.

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Much research has focussed on the effects of N deposition and specifically ammonia pollution on ecosystems, with experiments and national surveys finding links with reducing species richness, altered species composition and responses in individual species. There is also a desire to use ecological surveying to assess individual sites predicted to be at risk from ammonia pollution. In 2009-2010 Natural England commissioned a series of 53 ecological surveys of SSSI sites that were predicted, based on Environment Agency Modelled Risk Assessments, to be at risk of damage from ammonia pollution from a nearby intensive farming facility.

The objectives of this project were to: 1) review the findings of these ecological surveys using expert knowledge, 2) classify the sites into those with and those without evidence of effects consistent with ammonia impacts, 3) investigate the quality and attributes of site surveys, together with the site and farm characteristics to see if the difference in survey outcome could be explained, 4) Appraise the use of modelling assessments and site surveys in environmental permitting.

Of the 53 site surveys reviewed, 32 sites were found with evidence of impacts of ammonia, and 16 sites with no evidence of impacts. In 5 sites the evidence was unclear. Investigation of the survey and site characteristics found that surveys that targeted the recording of epiphytic lichens and/or ground flora were more likely to find evidence of eutrophication. We also found that the availability of historical data (e.g. previous vegetation surveys) influenced the likelihood of identifying eutrophication responses. Mean process contributions from nearby farms for sites with eutrophication responses were higher (mean 3.8 µg NH_3 m^{-3}) than those for sites with no response (0.98 µg NH_3 m^{-3}) and this difference was statistically significant. These NH_3 thresholds fit well with newly revised critical levels for NH_3.

We concluded that modelling assessments, including estimates of the process contributions and exceedance of critical levels and critical loads, can be used in environmental permitting to identify sites ***at risk*** from the adverse impacts of ammonia emissions (or nitrogen deposition) from intensive livestock units. However, modelling assessments do not provide evidence of damage. One-off botanical surveys provide baseline ecological data for detecting future change and can identify the presence of sensitive species and/or habitats which could be used to assist in the decision to issue a permit. However, they have limited value in the permitting of existing sites when used independently of other assessment methods as they are difficult to interpret and provide insufficient evidence to attribute site condition solely to nitrogen.