Assessment of the Impacts of Air Pollution on Ecosystem Services – Gap Filling and Research Recommendations

(Defra Project AQ0827)

Final Report

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Executive Summary

1) Building on previous work valuing impacts of air pollution (nitrogen, sulphur and ozone) on ecosystem services, this study aimed to:

   a) **WP1**: Review the evidence and data behind previous valuation studies of air pollution on ecosystem services.
   b) **WP2**: Apply an improved spatially explicit methodology to value impact of selected ecosystem services.
   c) **WP3**: Prioritise additional ecosystem services for valuation of air pollution impacts. Identify existing or planned projects and new research which might provide relevant information, and recommend appropriate research approaches to model them.
   d) **WP4**: Collate damage costs from this and previous studies.

2) **WP1**: A workshop of experts critically reviewed the impact pathways for twelve ecosystem services and the pollutants which affect them, covering the following aspects for each:

   a) Scientific understanding of the links between air pollution and ecosystem service;
   b) Dose response functions, or modelling capabilities to calculate those impacts.
   c) Valuation studies to monetise those impacts
   d) The ability to calculate impacts spatially, apply uncertainty analysis, and calculate damage costs

3) **WP2**: Four services were assessed to be ready for immediate valuation, spatially, for the UK, based on the following criteria: potential pollutant impact, strength of evidence for that impact, current ability to model that service, economic value of the service, relevance to air pollution policy. The first two services (in bold) were selected for analysis in this study.
   a) Ozone impacts on wheat production
   b) Nitrogen impacts on appreciation of biodiversity
   c) Nitrogen impacts on carbon sequestration in grasslands and heathlands
   d) Sulphur impacts on methane emissions

4) Quantification of marginal cost compared two scenarios: 1) Historical scenario: Changing nitrogen deposition/ozone flux between 1987 and 2007 against continuation of 1987 pollutant levels as a reference; 2) Future scenario: Projected nitrogen deposition/ozone flux from 2007 to 2020 against continuation of 2007 pollutant levels as a reference.

5) Difference in value of each service due to air pollution in each year was calculated, discounted at 3.5%, and Net Present Value (NPV), Equivalent Annual Value (EAV) and damage costs were calculated over the scenario periods. Uncertainty analysis was conducted spatially, using Monte Carlo simulations, presented as 95% Confidence Intervals.

6) Ozone impacts on wheat were calculated only for the future scenario, using the ozone flux metric of Phytotoxic Ozone Dose above a threshold of 6 nmol m^{-2} s^{-1}(POD_6) at 10 x10 km resolution. Valuation used a five-year average market price for wheat.
   - Loss of wheat production broadly replicates the spatial pattern of current wheat production, with ozone fluxes being highest in these areas.
   - There was a net cost to wheat production due to increasing ozone of -£18.6 million EAV (-£22.0m to -£15.4m, 95% CI) for the future scenario.
   - The damage cost per unit increase in ozone flux of POD_6wheat is -£100.6 million EAV (-£119.0m to -£83.4m, 95% CI) for the future scenario.
     Note that the marginal cost approach does not value the current impact of ozone on yield, relative to pre-industrial ozone concentrations. The absolute cost of UK ambient ozone

concentrations in 2007 on wheat yield was calculated as -£84.6 million, relative to zero POD6 (note: POD6 for wheat begins to accumulate at ozone concentrations above approximately 10 -15 ppb).
Further work could extend the marginal cost approach for two other crops: potato and oilseed rape, and should consider a range of models for calculating ozone flux

- Further discussion is needed on how to calculate damage costs for ozone as a secondary pollutant. Although ozone flux is the most scientifically accurate method currently available for valuation of effects related to vegetation, other ozone metrics, or relating ozone damage to emission of precursor chemicals could be explored.

7) Nitrogen impacts on Appreciation of biodiversity were calculated for the historical and future scenarios, for four habitats in the UK: acid grassland, dune grassland, bogs and heathland, using nitrogen deposition (kg N ha^{-1} yr^{-1}) at 5 x 5 km resolution. Valuation used value-transfer of stated preference (Willingness To Pay - WTP) values for increasing, or avoiding decline of, populations of non-charismatic species (plants, insects, etc.). Damage costs per tonne of NO_2 and NH_3 emitted were calculated for the future scenario. WTP values for charismatic species (animals, birds, butterflies) are a factor of 5 greater than for non-charismatic species, but impacts of N on those species cannot currently be modelled. This illustrates the importance of developing dose-response functions for charismatic species.

- Spatial impact reflected the occurrence of each habitat with respect to the spatial pattern of changes in N deposition.
- Declines in N deposition resulted in a combined benefit for 'appreciation of biodiversity' in the four habitats, for non-charismatic species. The mean EAV was £32.7m (£4.5m to £106.2m, 95% CI) in the future scenario, with the greatest increases in value occurring for heathland and for acid grassland habitats. The mean EAV was £14.9m in the historical scenario.
- Marginal damage costs of N impacts on 'appreciation of biodiversity' for nitrogen dioxide were £103/t NO_2 and for ammonia were £414/t NH_3 for the future scenario.
- The damage costs for nitrogen dioxide can be used in policy appraisal, since they reflect the result of large declines in emission and in deposition of oxidised N in the scenario evaluated.
- It is only recommended to use the damage costs for ammonia in policy appraisal where changes in emissions of reduced N are less than 10%. Relationships between N emission and deposition are non-linear and the scenario used in this study was based on only a 6% decline in emissions of reduced N. Therefore application to larger emission changes is not recommended.
- The damage costs for impacts on 'appreciation of biodiversity' can be applied for either increases or decreases in N emissions.
- Further work should aim to develop dose-response functions and apply valuation for impacts on charismatic species, calculate impacts for non-charismatic species in other habitats, and to conduct specific valuation studies focusing on impacts of air pollution.

8) **WP3**: Horizon scanning. Based on the expert knowledge of members of the consortium, the potential magnitude, the impact pathway and timescale to achieve valuation of impacts of air pollutants on ecosystem services was assessed.

9) From the horizon scanning, two further services were identified that could be valued in < 6 months:
-Valuing ozone impact on 2 crops (potato, oilseed rape) (Medium impact)
-Valuing sulphur impact on methane emissions (Small-Medium impact)
Valuation work on 19 other services would be possible in 6-24 months, shown in **Table ES1**.

10) **WP4:** Damage costs were collated from this and previous studies, shown in **Table ES2**. Reliability scores were assigned based on robustness of the impact pathway and dose-response functions,

and the ability to model impact spatially. Some previously calculated damage costs can be used for policy appraisal, while others are not sufficiently reliable for use in policy appraisal without further development.

11) Overall recommendations. This study has made considerable advances in modelling impacts on two services. Further work should aim to:

   a) Update the calculations and damage costs for previously valued services using the latest methodology.
   b) Construct and run meaningful scenarios for large-scale changes in ammonia emissions.
   c) Improve valuation of air pollution impacts on cultural services, using the horizon scanning to prioritise.

Table ES1: Magnitude of potential impacts of pollutants on ecosystem services and timescale to completion of valuation. *Note: where a range of time is presented, some aspects of the valuation can be completed before others, for example for C sequestration, it would be possible to complete valuation of effects on grasslands, woodlands, heath and peatlands at different stages within the 6 – 24 months time-scale.*

Service	Category	Nitrogen		Sulphur		Ozone	
		Potential Impact	Timescale to completion	Potential Impact	Timescale to completion	Potential Impact	Timescale to completion
Provisioning	Crop production - agriculture	Small	6 – 12 months	Small - Medium[1]	6 – 12 months	Medium	< 6 months (potato, oilseed rape) 12 - > 24 months other crops
	Crop production - biomass	Small	12 – 24 months	~	~	~	~
	Livestock production	Small	6 – 12 months	Small	6 – 12 months	Small - Medium	6 – 12 months
	Fisheries - shellfish	Small	12 – 24 months	~	~	~	~
	Timber production	Medium	6 – 24 months	Small	6 – 12 months	Medium	6 – 12 months
	Water supply	Small	12 – 24 months	Small	12 – 24 months	Small	12 – 24 months
Regulating	Flooding	Small	6 – 24 months	Small	6 – 24 months	Small-Medium	6 – 24 months
	Carbon sequestration	Medium - Large	6 – 24 months	Small - Medium[2]	6 – 24 months	Medium	6 – 24 months
	Methane emissions	Medium	12 – 24 months	Small - Medium[2]	3 – 12 months	Medium	6 – 12 months
	N_2O emissions	Medium - Large	6 – 12 months	~	~	Small	6 – 12 months
	Quality of drinking water	Small	6 – 12 months	Medium[2]	6 – 24 months	~	~
Cultural	Recreational fishing	Medium	3 – 6 months	Medium[2]	3 – 6 months	~	~
	Appreciation of biodiversity (aquatic)	Small-Medium	6 – 24 months	Medium[2]	6 – 12 months	~	~
	Appreciation of biodiversity (terrestrial)	Large	6 – 24 months (charismatic species)	Small	3 – 6 months	Medium	6 – 12 months
	Aesthetics ("early autumn")	~	~	~	~	Small - Medium	6 – >24 months

[1] reductions in S emissions have resulted in added S fertilizer requirements
[2] acidification effects of S are likely
~ Unknown or negligible impact

Table E4a,b. Collated damage costs plus uncertainty bounds from Defra air quality valuation reports, future emissions scenarios for a) NO_2, NH_3 and SO_2 (£ per tonne pollutant emitted in UK); b) Ozone (£ per unit ozone). Values in black are positive, showing a benefit from changes in pollutants (decreasing N, increasing ozone), values in red are negative, showing a cost due to changes in the pollutants (decreasing N, increasing ozone). n.v. = Not Valued. Rigour of value estimate: ## Robust, # Acceptable, (#) Improvements desirable and not currently acceptable for policy appraisal.

a)	*Provisioning Services*			*Regulating Services*				*Cultural Services*	
				Net GHG emissions					
	Crop production	**Timber production**	**Livestock production**	CO_2	N_2O	CH_4	**Clean water**	**Recreational fishing**	**Appreciation of biodiversity**
Decreasing Nitrogen dioxide	n.v.	-£4.3 (-£8.0 to -£2.3)[1] (#)	-£8.8 (-£11.8 to -£5.6)[1] (#)	-£54.0 (-£94.0 to -£22.8)[1] #	£11.8 (£6.2 to £18.7)[1] #	n.v.	n.v.	£0.1 (uncertainty not calculated)[1] (#)	£102.8 (£33.3 to £237.4)[3] ##
Decreasing Ammonia	n.v.	-£93.1 (-£170.7 to -£49.7)[1] (#)	-£294.1 (-£395.9 to -£186.6)[1] (#)	-£1,267.1 (-£2,204.0 to -£535.4)[1] #	£338.4 (£179.1 to £537.4)[1] #	n.v.	n.v.	£2.2 (uncertainty not calculated)[1] (#)	(£413.8) (£139.1 to £1,021.5)[3] ##
Decreasing Sulphur dioxide	n.v.	n.v.	n.v.	n.v.	n.v.	-£5.3 (-£1.6 to -£9.5)[1] #	n.v.	n.v.	n.v.

b)	*Provisioning Services*			*Regulating Services*				*Cultural Services*	
				Net GHG emissions					
	Crop production	**Timber production**	**Livestock production**	CO_2	N_2O	CH_4	**Clean water**	**Recreational fishing**	**Appreciation of biodiversity**
Increasing Ozone per unit 7-month 24-hr mean (ppb)	n.v.	n.v.	-£1,051,000 (-£1,705,000 to -£427,000)[2] ##	-£5,740,000 (-£7,939,000 to -£3,866,000)[2] ##	n.v.	n.v.	n.v.	n.v.	n.v.
Increasing Ozone per unit flux (POD)	-£100,555,000 (-£118,970,000 to -£83,421,000)[3] ##	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.

[1] Defra report NE0117, [2] Defra report AQ0815, [3] Defra report AQ0827 (this report)

Technical Summary

Introduction

Valuation of air pollution impacts on ecosystem services has been conducted for nitrogen, sulphur and ozone within Defra study NE0117 (Jones et al. 2012). Within that study, valuation of air pollution impacts was limited to semi-natural habitats and was primarily a proof of concept for testing the Ecosystem Services Approach. Subsequent work under study AQ0815 developed the methodology for spatially explicit calculation of ozone impact on three ecosystem services. Building on these and other previous studies valuing impacts of nitrogen, sulphur and ozone on ecosystem services, a need was identified to:

i) WP1. Review the evidence and data behind previous valuation studies to see if they can be improved, primarily with respect to spatial quantification of impact,

ii) WP2. Prioritise and identify a small number of ecosystem services for which an improved methodology can readily be applied on a spatial basis,

iii) WP3. Suggest research methodologies to model impacts on additional services. Conduct a horizon-scanning exercise to identify existing or planned projects, and suggest new research which might provide the relevant knowledge or data for further improvements to the valuation of air pollutant impacts on ecosystem services.

iv) WP4. Collate damage costs from this and previous studies. Apply latest damage cost calculations to draft report NE0117.

WP1. Critical review of impact pathways

A workshop of experts was held to critically review the impact pathways for twelve ecosystem services and the pollutants which affect them. Each impact pathway was assessed against the following criteria: the potential pollutant impact on the ecosystem service, the strength of evidence for that impact, the current ability to model that service, the financial value of the service, and its policy relevance from an air pollution policy perspective. These scores were used to derive a final priority ranking for detailed valuation work within this study (**Table TS1**).

Table TS1. Final priority ranking for detailed valuation work within this study.

Nitrogen	**Sulphur**	**Ozone**
Able to model now and High policy priority		
Biodiversity (terrestrial)	Methane emissions	Crop production
Carbon sequestration (heathlands and grasslands)		
Able to model with some further development; Medium to High policy priority		
Crop production (biomass crops)	Crop production	Crop production (potato, oilseed rape)
Livestock production	Livestock production	Livestock production (Beef, Dairy)
Carbon sequestration (woodlands)	Water quality	Methane emissions
N_2O emissions	Recreational fishing	Carbon sequestration (woodlands)
Water quality	Biodiversity (aquatic)	Biodiversity (terrestrial)

Recreational fishing		
Biodiversity (aquatic)		
Knowledge insufficient (ecosystem science and/or valuation) to currently model the service spatially		
Timber production	Timber production	Crop production (other crops)
Water supply	Water supply	Timber production
Flooding	Flooding	Water supply
Methane emissions	Carbon sequestration	Flooding
	Biodiversity (terrestrial)	Carbon sequestration (heathlands)

WP2. Quantification of selected services

Based on the outcomes of work package 1, four ecosystem services were categorised as top priority for spatial quantification of impact. Within the resources of the project, and in discussion with the Defra project officer, it was decided to work only on the first two services (in bold), aiming to spatially quantify the air pollution impact, to value that impact across the UK, and to produce damage costs for each pollutant. Reporting for each of these services is structured based on the Defra (2010) value transfer guidelines.

1. **Ozone on Crop production - Wheat**
2. **Nitrogen on Appreciation of biodiversity**
3. Nitrogen on Carbon sequestration in grasslands and heathlands
4. Sulphur on Methane emissions

Air pollution metrics

For ozone impacts on wheat we used a flux-based metric, POD_6, which takes into account the spatially and temporally changing effects of weather (temperature, light, humidity), soil moisture and plant factors on the amount of ozone taken up by the crop. This approach is more biologically relevant than concentration-based indices and is the preferred approach of the LRTAP Convention. Thus, this study provides an advance on previous approaches which used the UK mean AOT40 (a concentration-based index, contract NE0117 (Jones et al. 2012)), or the spatially varying growing season 24 hour mean ozone concentration to incorporate data for multiple species in contract AQ0815 (Jones et al. 2013). For nitrogen the measure of current N deposition (kg N ha^{-1} yr^{-1}) was used.

The scenarios used

Calculations of the impacts of ozone and nitrogen on the provision of ecosystem service are based on the specification of two scenarios:

- '***Historical emissions scenario***': based on spatially modelled nitrogen deposition for the period 1987 – 2007, using 1987 as a baseline; and
- '***Future emissions scenario***' based on spatially modelled ozone flux and modelled nitrogen deposition for the period 2007 – 2020, using 2007 as a baseline.

The scenarios essentially set out two 'what if' questions for air quality policy, in the context of rising background ozone concentrations and falling nitrogen deposition: (i) in retrospect, what has been the impact on ecosystem service value of changes in these pollutants since 1987; and (ii) looking forward, what will be the expected impact on ecosystem service values under forecast further changes in these pollutants. Under each scenario, difference from baseline was calculated with future values discounted at 3.5%. Net Present Value, Equivalent Annual Value (EAV) and damage costs per unit pollutant were then calculated. Note that declining nitrogen deposition can have positive or negative impacts depending on the service.

Data used
Ozone flux data (POD_6) were only available to run the future scenario for ozone. This used spatially explicit ozone flux at 10 x10 km produced by AEA using the OSRM-SOFM V26c model. Nitrogen deposition data were available to run both the historical and future emissions scenarios at 5x5 km resolution, from CBED deposition and from the FRAME model, calibrated to CBED deposition in 2008. Both ozone and nitrogen data were based on pollutant emissions under the UEP43 energy scenario. Data were scaled linearly between the start and end timepoints of each scenario comparison for each grid cell.

Uncertainty analysis
Uncertainty analysis was conducted spatially using Monte Carlo simulations. The assumptions are documented for each service, and results are presented with 95% Confidence Intervals.

Spatial quantification and value transfer of the ecosystem services
Results for the two services are summarised below:

Ozone on wheat production

- Wheat is one of the most ozone-sensitive crops, and this study confirms previous investigations (Mills et al., 2011, Mills and Harmens, 2011) showing that ozone affects yield of wheat in the UK.

- Impacts on wheat yield were assessed using the ozone flux metric specific to wheat, $POD_{6.}$

- Under a future ozone scenario, the loss of production due to increasing ozone replicates the spatial pattern of current wheat production with ozone fluxes being highest in those areas where wheat is extensively grown.

- There was a net cost to wheat production due to increasing ozone of -£18.6 million EAV (-£22.0m to -£15.4m, 95% CI) for the future scenario.

- The damage cost per unit increase in ozone flux of POD_6wheat is -£100.6 million EAV (-£119.0m to -£83.4m, 95% CI) for the future scenario.

  It should be borne in mind that in using the marginal cost approach the difference in flux between 2007 and 2020 was relatively small, resulting in a relatively small economic cost as EAV per annum. Calculating the absolute cost in a single year, relative to zero ozone POD6, the 2007 ambient ozone concentration results in ozone fluxes that are detrimental to yield with a net cost of -£84.6 million. Note: POD6 for wheat begins to accumulate at ozone concentrations above approximately 10 -15 ppb.

- The key assumptions in this study were: The areas where wheat is grown, and determinants of yield other than ozone do not change between 2007 and 2020; The response function for wheat is applicable to current UK cultivars; UK farm-gate wheat prices was based on a five year average (2005-2009), subject to discounting; The three years used to estimate baseline impact (2006, 2007 and 2008) are representative years for current ozone flux; The future scenario used assumes compliance with existing legislation by 2020 and effects of climate change were not included; The spatial variation in ozone flux does not change between 2007 and 2020; The OSRM-SOFM model is equally accurate for all years and can accurately model ozone fluxes at/close to the threshold for flux accumulation (Y=6 nmol m^{-2} s^{-1}).

- Recommendations for further work include for wheat: New field-based ozone experiments with current cultivars; Testing of flux model parameterisation with current UK cultivars; Inclusion of projections of effects of climate change on wheat areas, wheat production, and ozone concentration and flux in the calculations; Expanding the range of years for which ozone flux is calculated to five for both the current and future scenarios; Consideration of use of other models available for the UK for ozone flux, including the Eulerian EMEP4UK model adapted for the UK from the EMEP model being used by the LRTAP Convention. Flux-based response functions are also available for use now for potato and oilseed rape. Spatial modelling of these crops could be conducted as for wheat, and new experiments for other crops could be conducted to facilitate development of flux-effect relationships, thereby increasing the range of crops studied.

- In order to calculate flux-based damage costs for ozone in new policy situations, the relevant flux-based measures (e.g. POD_6wheat) need to be calculated for each scenario. Further discussion is needed on how to calculate damage costs for ozone as a secondary pollutant. Although ozone flux is the most scientifically accurate method currently available for valuation of effects related to vegetation, the possibility of using other ozone metrics, or relating ozone damage directly to emissions of precursor chemicals could be explored.

Nitrogen on terrestrial biodiversity

- Increasing nitrogen causes a decline in plant species richness in a large number of UK habitats, including acid grassland, sand dune grassland, mixed grassland, heaths, bogs, deciduous woodland.

- Based on a previous study (Caporn et al. 2012), dose-response relationships for nitrogen deposition on species richness were derived for four of these habitats: heathland, acid grassland, sand dune grassland and bogs. Details of the equations are provided in Appendix C.

- Spatially explicit calculations were made for individual grid cells at 5x5km resolution. For each of the four habitats, in each grid cell, in each year, expected species richness was calculated based on the N deposition for that cell.

- Percentage difference in species richness from the reference year for that scenario was then calculated.

- Value transfer utilised Willingness To Pay (WTP) values from a Choice Experiment (Christie and Rayment, 2012) for maintaining or increasing populations of non-charismatic species (plants, insects, etc.). Values were scaled according to the proportional change in species richness for each specified habitat. WTP values for charismatic species (animals, birds, butterflies) are a factor of 5 greater than for non-charismatic species, but impacts cannot currently be modelled. There is evidence of N impacts on some charismatic species, therefore this remains a major gap in the valuation assessment.

- Declines in N deposition resulted in a combined benefit for appreciation of biodiversity in the four habitats with a mean EAV of £32.7m (£4.5m to £106.2m, 95% CI) in the future scenario. Heathland and acid grassland showed the greatest increases in value. Results are broken down by country for the UK (**Table TS2**). Uncertainty analysis was not run for the historical scenario, but the deterministic mean EAV was £14.9m for the historical scenario, suggesting values were lower by around 50%, due to the smaller decline in N deposition in this scenario.

- Marginal damage costs of N impacts on 'appreciation of biodiversity' for nitrogen dioxide were £103/t NO_2 and for ammonia were £414/t NH_3 for the future scenario.

- The damage costs for nitrogen dioxide can be used in policy appraisal, since they reflect the result of large declines in emission and in deposition of oxidised N in the scenario evaluated.

- It is only recommended to use the damage costs for ammonia in policy appraisal where changes in emissions of reduced N are less than 10%. Relationships between N emission and deposition are non-linear and the scenario used here was based on only a 6% decline in emissions of reduced N. Therefore application to larger emission changes is not recommended.

- The damage costs for impacts on 'appreciation of biodiversity' can be applied for increases or decreases in N emissions.

- Linking WTP directly to changes in species richness represents an improvement in the methodology of the previous study, but still holds large assumptions. The main assumptions are: declines in N deposition cause immediate increase in species richness, without lags – in practice lags will occur. They also ignore hysteresis and permanency effects, i.e. recovery to a previous state may not happen at all.

- Recommendations for further work include: Develop dose response functions for charismatic species and apply valuation for them; further refinement of the dose response relationships for non-charismatic species could be undertaken, including response functions for other habitats such as broad-leaved woodland and neutral grasslands; conduct specific valuation studies for assessing air pollution impacts on biodiversity.

Table TS2. Equivalent Annual Value of nitrogen impacts on appreciation of biodiversity for non-charismatic species, by country and by habitat, future scenario (95% Confidence Intervals).

Equivalent Annual Value	Acid grassland	Heathland	Dunes	Bogs	**Total 4 habitats**
England	£2,951,000	£4,058,000	£93,000	£1,239,000	**£8,341,000**
Wales	£1,886,000	£931,000	£26,000	£162,000	**£3,006,000**
Scotland	£7,309,000	£11,736,000	£106,000	£1,428,000	**£20,580,000**
Northern Ireland	£114,000	£424,000	£8,000	£203,000	**£749,000**
UK (95% CI)	**£12,260,000 (£1,800,000 to £39,900,000)**	**£17,150,000 (£2,700,000 to £56,000,000)**	**£234,000 (£10,000 to £820,000)**	**£3,033,000 (£300,000 to £10,700,000)**	**£32,676,000 (£4,400,000 to £109,700,000)**

WP3. Horizon scanning

Based on the expert knowledge of members of the consortium, the potential magnitude and pathway and timescale to valuation of impacts of air pollutants on ecosystem services was assessed. A summary is provided in **Table ES1** in the Executive Summary. Across the three air pollutants, and pending outcomes from ongoing research, two further services were identified that could be valued in < 6 months: ozone impact on 2 crops (potato, oilseed rape) (Medium impact), sulphur impact on methane emissions (Small-Medium impact). It should be possible to make significant advances in modelling a further 19 services within the next 24 months. For each of these services, the main methodological improvements and potential data sources are described.

WP4. Collation of damage costs

Collated damage costs from this and previous Defra studies are shown in **Table ES2ab** in the Executive Summary. Reliability scores were assigned based on robustness of the impact pathway and dose-response functions, and the ability to model air pollution impacts spatially. Reasons for differences in the 'appreciation of biodiversity' values between the reports include: Different set of habitats modelled, different valuation studies and methodology used for value transfer, improved spatial modelling of impact, different scenarios and nitrogen emission and deposition input data. Differences in the ozone values reflect an improved methodology in this study, including use of the more biologically relevant ozone flux metric relating impacts to the amount of ozone taken up by plants rather than to the concentration in the air above plants. Use of ozone flux-based metrics requires each metric to be calculated in future modelling scenarios in order to calculate damage costs. Although not all previous damage costs were based on spatial calculation of impact, some are considered robust enough for use in policy appraisal although they should be brought to the standard of the current methodology when the chance arises. Others however are not sufficiently reliable at present and require improvements in dose-response functions or valuation, as well as spatial calculation of impact before they can be used (**Table ES2**).

Overall recommendations

This study has made considerable advances in modelling impacts on two services. Further work should aim to:

- Update the calculations and damage costs for previously valued services using the latest methodology. This should incorporate more recent scenario emissions and deposition, and spatial analysis of impact on ecosystem services.
- Construct and run meaningful scenarios for large-scale changes in ammonia emissions. Until this is done, the damage costs for NH_3 developed under the current scenario should only be applied where emission changes are < 10%.
- Improve valuation of air pollution impacts on cultural services and regulating services where pollution has an adverse impact, using the horizon scanning to prioritise.

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Glossary

These definitions are taken from a range of web resources including Wikipedia and OECD statistics definitions[1], with italics clarifying usage in this study.

24-hour mean ozone – Mean ozone concentration calculated over a 24 hour period. In a previous study (Jones et al. 2013), the ozone metric used was average 24-hour mean over a seven-month growing season, March to September inclusive.

AOT40 – Accumulated Ozone over a Threshold of 40 ppb (hourly means calculated during daylight hours), unit: ppb hours.

Charismatic species – As defined in Christie and Rayment (2011): threatened animals, amphibians, birds and butterflies species and populations that will be influenced by UK Biodiversity Action Plan implementation. *See also non-charismatic species.*

Damage cost - The cost incurred by repercussions (effects) of direct environmental impacts (for example, from the emission of pollutants) such as the degradation of land or human—made structures and health effects. In environmental accounting, it is part of the costs borne by economic agents. *Here it is expressed as the marginal damage cost, i.e. the damage cost per unit pollutant emitted (or per unit change in ozone flux).*

Discount rate - The discount rate is an interest rate used to convert a future income stream to its present value.

Equivalent Annual Value (EAV) - The net present value (NPV) of the change in ecosystem service occurring due to a scenario, divided by an annuity factor calculated over the duration of the scenario.

Marginal Cost - Marginal cost is the increment to total cost that results from producing an additional unit of output.

Monte Carlo analysis - Computational algorithms that rely on repeated random sampling to obtain numerical results; i.e., by running simulations many times over in order to calculate those same probabilities. *In this study they are used to model uncertainty in the outcomes by incorporating known sources of uncertainty or variability in inputs.*

Net Present Value (NPV) - Valuation method to value stocks of natural resources. It is obtained discounting future flows of economic benefits to the present period.

Non-charismatic species – As defined in Christie and Rayment (2011): Threatened trees, plants, insects and bug species and populations that will be influenced by UK Biodiversity Action Plan implementation. *See also charismatic species.*

POD_6 - Phytotoxic Ozone Dose above a threshold flux of 6 nmol m^{-2} s^{-2}. This parameter describes the accumulated stomatal flux of ozone above a threshold flux for wheat, which takes account of natural detoxification mechanisms in plants that reduce the toxic effect of ozone. The unit of accumulated flux above the threshold is mmol m^{-2}.

Stomatal flux of ozone – The ozone actually taken up by the plant through the stomata, rather than the concentration of ozone in the surrounding air.

UEP43 – Updated Energy Projections 43 energy forecasts published in October 2011.

[1] http://stats.oecd.org/glossary/search.asp

1 Introduction

1.1 Background

Nitrogen is a global pollutant, with levels of reactive nitrogen (N) in the atmosphere increasing since the 1940s as a result of man's activities (Galloway et al., 2008). The main sources of oxidised N compounds are vehicle emissions, industry and domestic combustion, while reduced N compounds, primarily ammonia, derive from agriculture sources such as manure and fertiliser volatilisation. Nitrogen is a basic nutrient required for growth, and most semi-natural systems are N-limited (Vitousek et al., 1997). Increased N deposition in the last 70 years has caused widespread adverse impacts on biogeochemical cycling and biodiversity in semi-natural systems as a result of both eutrophication and acidification, which have been well studied (e.g. Phoenix et al., 2012). However, since N stimulates plant growth, deposition of this nutrient may be seen as beneficial for human production systems, e.g. by increasing forest growth (de Vries et al., 2009). Across Europe, emissions of N have now declined by 25% since around 1990 due to policy measures to reduce industrial and vehicular emissions of oxidised N, and to reduce ammonia emissions from agriculture. However, the effect of this decline in emissions has not been systematically evaluated across a wide range of sectors.

Sulphur emissions derive mostly from fossil fuel burning. The impacts of S emissions and deposition on terrestrial productivity are complex, and to some extent conflicting. At high deposition levels it causes acidification and decreases productivity, at low deposition levels its role as a secondary plant macronutrient means it is required for crop and semi-natural vegetation growth. Sulphur-associated acidification has important, policy-relevant, consequences for biogeochemical cycling in semi-natural ecosystems, with impacts on streamwater chemistry and knock-on effects on aquatic biodiversity, and impacts on greenhouse gas emissions.

Ozone is a powerful oxidative pollutant causing widespread damage to crops and native vegetation (Ashmore, 2005). Levels of tropospheric ozone have significantly increased within industrialised nations since the middle of the last century (Vingarzan, 2004). It is predicted that by 2050 the mean global surface ozone concentration will increase by 23% of today's levels (Morgan et al., 2006) and by 2100 annual mean ozone concentrations are likely to exceed 75 ppb over most of Europe and exceed 90 ppb in large parts of South America, Africa and South East Asia (Sitch et al., 2007), in comparison with typical rural UK background concentrations of 25-35 ppb (ROTAP, 2012). A particular concern is the increase in background ozone concentrations (Derwent et al., 2007) caused by the long-range transport of many ozone precursors, leading to increased ozone concentrations in rural areas and impacts on semi-natural or natural vegetation types.

Valuation of air pollution impacts on ecosystem services has been conducted for nitrogen, sulphur and ozone within a previous Defra study NE0117 (Jones et al. 2012). Within that study, valuation of air pollution impacts was limited to semi-natural habitats and was primarily a proof of concept for testing the Ecosystem Services Approach. Quantification and valuation of impacts was conducted using UK average pollutant deposition or concentrations, and did not take into account spatial context. For ozone, a previous study (Mills et al., 2011) calculated spatial effects on crop yield using farm gate prices for two contrasting ozone years: 2006 with relatively high ozone concentrations throughout the growing season and 2008 with lower concentrations in the summer. A subsequent Defra study AQ0815 (Jones et al. 2013) has developed the spatial quantification of the marginal cost of ozone on ecosystem services for three ecosystem services: carbon sequestration, lamb production and appreciation of biodiversity as examples. Building on these and other previous work valuing impacts of nitrogen, sulphur and ozone on ecosystem services, a need was identified to:

i) Review the evidence and data behind previous valuation studies to see if they can be improved, primarily with respect to spatial quantification of impact,

ii) Prioritise and identify a small number of ecosystem services for which an improved methodology can readily be applied on a spatial basis,
iii) Conduct a horizon-scanning exercise to identify existing or planned projects which might provide relevant knowledge or data for further improvements to the valuation of air pollutant impacts on ecosystem services.

Following methodological advances, the project scope was extended to include the following:
iv) Collate damage costs from this and previous studies, apply updated damage cost methodology to the draft report Jones et al. (2012 Draft), and release the report.

The project had the following objectives, which were broken down into four work packages as detailed below.

Objectives:

1. To further enhance Defra's (The Authority) current valuation of air pollution impacts on ecosystem services.

2. To identify and prioritise further research requirements to address evidence gaps, focussing on the impacts of air pollutants on ecosystem services

The following detailed descriptions are adapted from the tender document and subsequent project extension:

Work Package 1. Summarise evidence gaps

This work package should draw heavily on Jones et al. (2012) rather than starting from first principles. It shall summarise key gaps in the assessment of air pollution impacts on ecosystem services. It shall then identify where the "quick wins" are, i.e. where these gaps can be filled during the course of this project, and which require further work and/or research.

- *Summarise the key gaps in the assessment of air pollution impacts on ecosystem services. This includes presenting which ecosystem services were omitted from the subset used in the Jones et al. study (2012) but which may be "important" to the overall assessment and valuation, and which services were included, but where there were limitations in the approach (e.g. a spatial assessment; or assumptions made about dose response).*

- *Identify which 'gaps' can be addressed during the course of this study, which need tackling over longer-term but broadly speaking for which the evidence is there to support this (possibly requiring some re-analysis), or those which require new research.*

Work Package 2. Develop the assessment

The study by Jones et al. (2012) did not provide a full assessment of air pollution impacts on ecosystem services since its purpose was to demonstrate the practical application of a methodology for valuing the ecosystem service impacts of air pollution. It therefore included only a subset of impacts on subset of ecosystem services and did not undertake a full spatial assessment of impacts. In this study we seek to further enhance the assessment by applying a spatial assessment of impacts on services and increasing the number of services assessed if possible within the short timescale of the project.

- *Based on the findings of Work Package 1, undertake further work to improve the recent assessment of impacts on ecosystems services by Jones et al. (2012) by addressing the key gaps in their approach as well as "important" ecosystem services which were excluded from the selected sub-set, but for which supporting information is readily available. For example a spatial assessment and any other areas identified by the contractor. This includes calculation of damage costs for the services selected.*

Work Package 3. Identify and prioritise further research requirements

This work package will identify research requirements to address remaining evidence gaps. Whilst there may be many gaps in our scientific understanding of the processes underpinning our assessment of the relative impacts on ecosystems services of different air pollution policies, the study should identify which are important in terms of the ultimate goal to monetise the impacts.

- *Using the findings of Work Package 1, establish criteria, and apply them, to prioritise the gaps in evidence/gaps in scientific understanding of air pollution impacts on ecosystem services.*
- *Recommend approaches or research which can address these gaps in the short term or a longer-term research programme.*
- *Make the link to, and recommend synergies with, other established initiatives or programmes of research and development in this area whose primary aim may not be air pollution impacts on ecosystem services, but which may help address some of the identified gaps either directly or through additional collaborative research.*

Work Package 4. Summarise evidence gaps

This work package draws together information from previous Defra studies. It will collate damage costs from this study and previous Defra projects NE0117 and NE0815, and assign reliability scores to these. This will include the update and finalisation of report NE0117.

1.2 Structure of the report

This report covers the four workpackage requirements outlined above. After the introduction, the first section (section 2) describes the outcomes from an expert workshop evaluating knowledge gaps in the current methodologies of quantifying air pollution impacts on ecosystem services, and prioritising services for future research (work package 1).

The following section (section 3) reports on work package 2, and provides technical detail of quantifying the impact of two air pollutants and services agreed with Defra as a result of outcomes from the expert workshop:

- Ozone impacts on wheat production.
- Nitrogen impacts on biodiversity.

For each service, it describes how dose-response functions were derived and applied to calculate air pollution impacts on the environmental and ecosystem service component of the impact pathway in a spatially-explicit context. It also provides technical details of the value transfer analysis and describes how uncertainty in the valuation was addressed in each case. Damage costs are also calculated for each pollutant and service. The reporting structure for each of these services is based on the Defra (2010) value transfer guidelines:

- ***Summary - aggregate estimates for the valuation of the change in the provision of the policy good***: the 'headline' results for the analysis are presented initially, together with a brief summary of the methodology. This section of the reporting is based on Steps 6 and 7 of the Defra value transfer guidelines.

- ***Definition of the policy good***: a summary of the good, its characteristics and the types of use and non-use value is provided. This sets out the main elements of the impacts of air pollution on ecosystem service provision that are estimated in monetary terms. Discussion is provided for impacts that are not monetised. Assumptions as to the affected population are also set out. This section of the reporting is based on Step 2 of the guidelines.

- ***Estimating the change in provision of the policy good***: a summary of the analysis undertaken to estimate the physical impact of air pollution on ecosystem service provision. This section of the reporting is based on Step 3 of the guidelines and draws on the more detailed assessment of scientific understanding of the impact pathway and evidence presented in Defra study NE0117 (Jones et al. 2012).

- ***Selection of value transfer evidence***: the valuation evidence applied in the analysis is presented and its selection detailed in terms of the criteria presented in Step 4 for the guidelines.

- ***Application of value transfer***: details of the actual economic values used in the analysis estimation of aggregate costs and benefits are presented following Steps 5 and 6 of the guidelines.

- ***Key assumptions and caveats***: discussion of key sensitivities in the analysis and the main limitations and uncertainties, following Step 7 of the guidelines.

- ***Recommendations for further work***: the reporting concludes with discussion of recommendations for further work, based on the progress achieved in this study, the assumptions and caveats made, and ongoing knowledge of other work which may guide further improvements in the methodology.

The next section of the report (section 4) presents the horizon scanning component (work package 3), identifying current and upcoming projects which may broaden or improve the ability to calculate air pollution impacts on ecosystem services in future.

The final section (section 5) collates all damage costs calculated under this and previous Defra contracts, assigns reliability scores and discusses reasons for the differences between them.

2 WP1. Gap analysis

This section aimed to work on the three air pollutants studied by Jones et al. (2012): nitrogen compounds (oxidised and reduced N), sulphur dioxide, and tropospheric ozone. It focused on the same quantification and valuation methodology for assessing impacts on ecosystem services, i.e. on the impact pathway, seeking to improve it on the basis of advances in the conceptual understanding of how ecosystem services are delivered and in how air pollution impacts on ecosystem function and processes. The impact pathway for each ecosystem service was critically reviewed by a panel of experts as described below.

A workshop was held on 29th April 2013 to critically review the impact pathway for each pollutant impact on each ecosystem service. In addition to the six key ecosystem services selected for detailed study in Jones et al. (2012), the workshop reviewed the conceptual links and the potential evidence for all ecosystem services identified in Annex 1 of the previous study (Jones et al., 2012, Annex 1), and also included evidence for impacts on crops, drawing partly on a subsequent study (Jones et al. 2013). The full tables of information that was available for each service can be found in Appendix A.

The synthesis of the workshop findings is shown in Table 1 below where, based on the information available for each service a range of criteria were scored. These were: the potential pollutant impact on the ecosystem service, the strength of evidence for that impact, the current ability to model that service, the financial value of the service, its policy relevance from an air pollution policy perspective. Key notes on each service are also included for information.

In discussion with the project officer and other Defra staff, these criteria were combined, taking into account information for each, in order to assign a final priority weighting score for each service (last column in Table 1). The final decision score grouped the pollutant-service combinations into 3 categories:

1) Able to model now, high impact and/or financial value, and high air pollution policy relevance.
2) Able to model with some further development of response functions and collation of ecosystem data and valuation studies; medium to high impact and/or financial value, and medium to high air pollution policy relevance.
3) Ecosystem science and/or valuation knowledge insufficient to currently model the service. May be low to high impact and/or financial value, and air pollution policy relevance.

This was used to select which services were to be spatially quantified in work package 2.

Table 1. Summary scores to determine priority for modelling each ecosystem service and pollutant.

Potential impact on the ecosystem service, Ability to model, Financial value, Relevance for air pollution policy: (L=Low, M=Medium, H=High); Strength of evidence: ((#) = Expert judgement/Anecdotal, # = Published evidence/grey literature 1 or 2 studies, ## = Published evidence >2 studies); Final priority order: 1 = Able to model now and high policy priority, 2 = Able to model with limited further development and medium to high policy priority, 3 = Ecosystem science and/or valuation knowledge insufficient to currently model the service.

Service	Impact	Strength of evidence	Ability to model	Financial value	Relevance for air pollution policy	Notes	Final priority order
Provisioning Services							
Crop Production							
Nitrogen	Low	(#)	Low/Med	High	High	May be important for biofuel crops - Food security	2
Sulphur	Med	(#)	Med	High	Med	Increasingly important, but need to know crop requirements of S- Food security	2
Ozone	**High**	**##**	**High**	**High**	**High**	**Possible now. High impact, high value. - Food security**	**1**
Livestock Production							
Nitrogen	Low	(#)	Med	Low-High	Med/High	Financial impact depends on livestock type. - Food security	2/3
Sulphur	Low	(#)	Med	Low-High	Med	Financial impact depends on livestock type - Food security	2/3
Ozone	Low	#	Low/Med (Cattle) High (Lambs)	Low-High	Med/High	Financial impact depends on livestock type - Food security	2 (Cattle) Done[2] (Lambs)
Timber Production							
Nitrogen	Low/Med	#	Low/Med	Low	Med	Timber production currently low economic value - only timber considered here, but note synergies with C sequestration	3
Sulphur	Low/Med	#	1	Low	Low	Timber production currently low economic value	3
Ozone	Med	##	Low/Med	Low	Med	Timber production currently low economic value	3
Water supply							
Nitrogen	Low	(#)	Low	Low	Low	Low evidence, impact and value, Med/High policy	3

[2] Using 24-hour mean ozone, over a seven-month growing season

Service	Impact	Strength of evidence	Ability to model	Financial value	Relevance for air pollution policy	Notes	Final priority order
Sulphur	Low	(#)	Low	Low	Low	Low evidence, impact and value, Med/High policy	3
Ozone	Low	(#)	Low	Low	Low	Low evidence, impact and value, Med/High policy	3
Regulating Services							
Water regulation (river flooding)							
Nitrogen	Low	(#)	Low	Low	Low	Low evidence, impact and value, High policy interest	3
Sulphur	Low	(#)	Low	Low	Low	Low evidence, impact and value, High policy interest	3
Ozone	Low	(#)	Low	Low	Low	Low evidence, impact and value, High policy interest	3
Quality of water for drinking							
Nitrogen	Low	(#)	Med	Low	Med/High	Some work required to develop response functions and upscaling	2
Sulphur	Med	#	Med	High	Med/High	Some work required to develop response functions and upscaling	2
Carbon sequestration							
Nitrogen	**High**	**#**	**Med (Woodlands, bogs) High (Heathlands, grasslands)**	**High**	**High**	**Some habitats ready to model, others particularly woodland, need more work**	2 (Woodlands, bogs) **1 (Heathlands, grasslands)**
Sulphur	Low	#	Low	High	Low	Negligible impact.	3
Ozone	High	(#) ## ##	Low (Heathlands) Med (Woodlands) High (Grasslands)	High	High	Some habitats ready to model, others particularly woodland, need more work, - parallel work ongoing	2 (Heathlands) 2 (Woodlands) Done[3] (Grasslands)
Methane Emissions							
Nitrogen	Low	(#)	Low	High	High	Requires predictions of habitat change	3

[3] Using 24-hour mean ozone, over a seven-month growing season

Service	Impact	Strength of evidence	Ability to model	Financial value	Relevance for air pollution policy	Notes	Final priority order
Sulphur	**Med**	**#**	**High**	**High**	**Med/High**	**Possible now, medium impact, high value**	**1/2**
Ozone	Low	(#)	1/Med	High	High	Possibly some consensus emerging on dose-response, but not available yet	2
N_2O Emissions							
Nitrogen	Low	#	Med	High	Med/High	Wait until new soil emission factors have been developed. Otherwise methodology already developed	2
Cultural Services							
Recreational fishing							
Nitrogen	Low	(#)	Med	High	Med	Some work required to develop response functions and upscaling	2
Sulphur	Med	##	Med	High	Low/Med	Some work required to develop response functions and upscaling	2
Appreciation of biodiversity (aquatic)							
Nitrogen	Med/High	##	Med	High	High	Some work required to develop response functions and upscaling	2
Sulphur	Med/High	##	Med	High	Low/Med	Some work required to develop response functions and upscaling	2
Appreciation of biodiversity (terrestrial)							
Nitrogen	**High**	**##**	**High**	**High**	**High**	**Possible now, high impact, high value**	**1**
Sulphur	Low	(#)	Low	High	Low	Little evidence for dose response functions	3
Ozone	Med	#	Med	High	High	Needs further development of response functions	2

3 WP2. Quantification of selected services

3.1 Introduction.

Based on the outcomes of work package 1 (Table 1), four ecosystem services were prioritised for spatial quantification of impact. These were, in order of priority:

- Ozone on Crop production
- Nitrogen on Appreciation of biodiversity
- Nitrogen on Carbon sequestration in grasslands and heathlands (woodlands requires more detailed input on forest production systems)
- Sulphur on Methane emissions

Within the resources of the project, and in discussion with the Defra project officer, it was decided to work only on the first two services, aiming to spatially quantify the air pollution impact, to value that impact across Great Britain, and to produce damage costs for each pollutant, where possible. The rest of the section presents the methodology and results for these two services.

3.2 Scenarios used in the marginal cost analysis

Quantification and valuation of impact used the marginal cost approach, comparing impacts under one pollutant scenario with those under a reference (counter-factual) scenario. Two scenario comparisons were made, a historical emissions scenario and a future emissions scenario. This section describes the methodology undertaken.

3.2.1 Ozone metric used

The choice of metric is very important in evaluating impacts of air pollutants. For ozone impacts on wheat we used a flux-based metric, POD_6 (Phytotoxic Ozone Dose over a threshold flux of 6 nmol m^{-2} s^{-1}), described in more detail below, which takes into account the spatially and temporally changing effects of weather (temperature, light, humidity), soil moisture and plant factors on the amount of ozone taken up by the crop. This approach is more biologically relevant than concentration-based indices and is the preferred approach of the LRTAP Convention. Thus, this study provides an advance on previous approaches which used the UK mean AOT40 (a concentration-based index which measures the accumulated ozone concentration above a threshold of 40 ppb, used in Jones et al. 2012), or the spatially explicit growing season 24 hour mean ozone concentration, used in Jones et al. (2013). It also facilitates comparison with the study by Mills et al. (2011) which used both AOT40 and POD_Y for three crops (wheat, potato and oilseed rape) for 2006 and 2008, using farm-gate values to spatially quantify impacts. Selection of the POD_6 metric meant that it was only possible to calculate impacts for the future ozone scenario as modelled ozone flux data were not available for time periods in the historical ozone scenario. Note that individual crops will have different flux models and possibly different flux thresholds. Therefore the flux metric needs to be modelled for each crop in any new situation.

The first stage in impacting on crop production is the transfer of ozone through the atmosphere and into the plant via the thousands of microscopic stomatal pores on the leaf surface. Firstly, atmospheric processes above the plant canopy such as wind turbulence and the roughness of the terrestrial landscape control the transfer of ambient ozone towards the vicinity of the leaf surface. At the leaf surface the thickness and resistance of the boundary air layer around the leaf to ozone transfer depends primarily on wind speed and leaf characteristics such as orientation, size, shape and hairiness. Once through the boundary layer, ozone entry into the plant is dependent upon how open the stomatal pores are. The stomata normally open or close to control CO_2 exchange with the outside air during photosynthesis and respiration, and/or to control water loss from the plant, depending on environmental conditions. Thus, the more open the stomata are, the more ozone will enter the plant. Stomatal flux of ozone is not only determined by the ozone concentration in ambient air but also by other factors such as light, air temperature and humidity (vapour pressure deficit: VPD), soil water potential (SWP) or plant available water (PAW), and plant developmental stage (phenology). It is modelled using the algorithm contained in Box 3.1 incorporating species-specific parameterisations for the effects of the various climatic, soil water and growth stage factors on the maximum stomatal conductance (LRTAP Convention, 2010). Analysis of impacts of ozone on crops is based on the accumulated stomatal flux above a threshold flux, with the threshold flux incorporated to take account of natural detoxification mechanisms in plants that reduce the toxic effect of ozone. The flux parameter used is the Phytotoxic Ozone Dose above a threshold of Y, POD_Y.

Chemical transport models are used to estimate the temporal distribution of ozone flux in the UK. These fall broadly into two groups dependant on approach used: Lagrangian and Eulerian. In simple terms, Lagrangian models calculate ozone distribution from the trajectories of a large number of individual parcels of air whereas Eulerian models use a fixed three dimensional frame of reference and compute the temporal changes in concentration within each grid cell from the physical and chemical compositions. Both approaches have advantages and disadvantages, with several variants in use (Monks et al., 2007). The LRTAP Convention uses the Eulerian approach within the EMEP model for mapping ozone concentrations and fluxes across Europe, and a UK version of the EMEP model (EMEP4UK) has been developed. For this study, a Lagrangian model developed by AEA was used as this model is currently in use for policy work related to the health impacts of ozone and its use facilitates cross referencing between predictions for effects on health and ecosystems. Thus, to model spatial and temporal changes in ozone flux across the UK, the AEA Ozone Source Receptor-Surface Ozone Flux model (OSRM-SOFM) was used in combination with the SEI ozone deposition to vegetation (DO_3SE) model. It has been noted, however, that the OSRM-SOFM model tends to underestimate ozone concentration and flux in the dry years such as 2006 (Abbott and Cooke, 2010).

3.2.2 Nitrogen metric used

For nitrogen impacts, the standard measure of N deposition (kg N ha^{-1} yr^{-1}) was used as the metric of pressure, and to derive dose-response relationships. For the marginal damage cost calculations, the impact would need to be separately calculated for oxidised and reduced forms of nitrogen, using the same units. Other N metrics are currently being considered in Defra projects (Defra project AQ0823), for pressure metrics and damage metrics.

3.2.3 Description of scenarios

Calculations of the impacts of ozone and nitrogen on the provision of ecosystem service are based on the specification of two scenarios:

- '***Historical emissions scenario***': based on spatially modelled nitrogen deposition for the period 1987 – 2007, using 1987 as a baseline; and
- '***Future emissions scenario***' based on spatially modelled ozone flux and modelled nitrogen deposition for the period 2007 – 2020, using 2007 as a baseline.

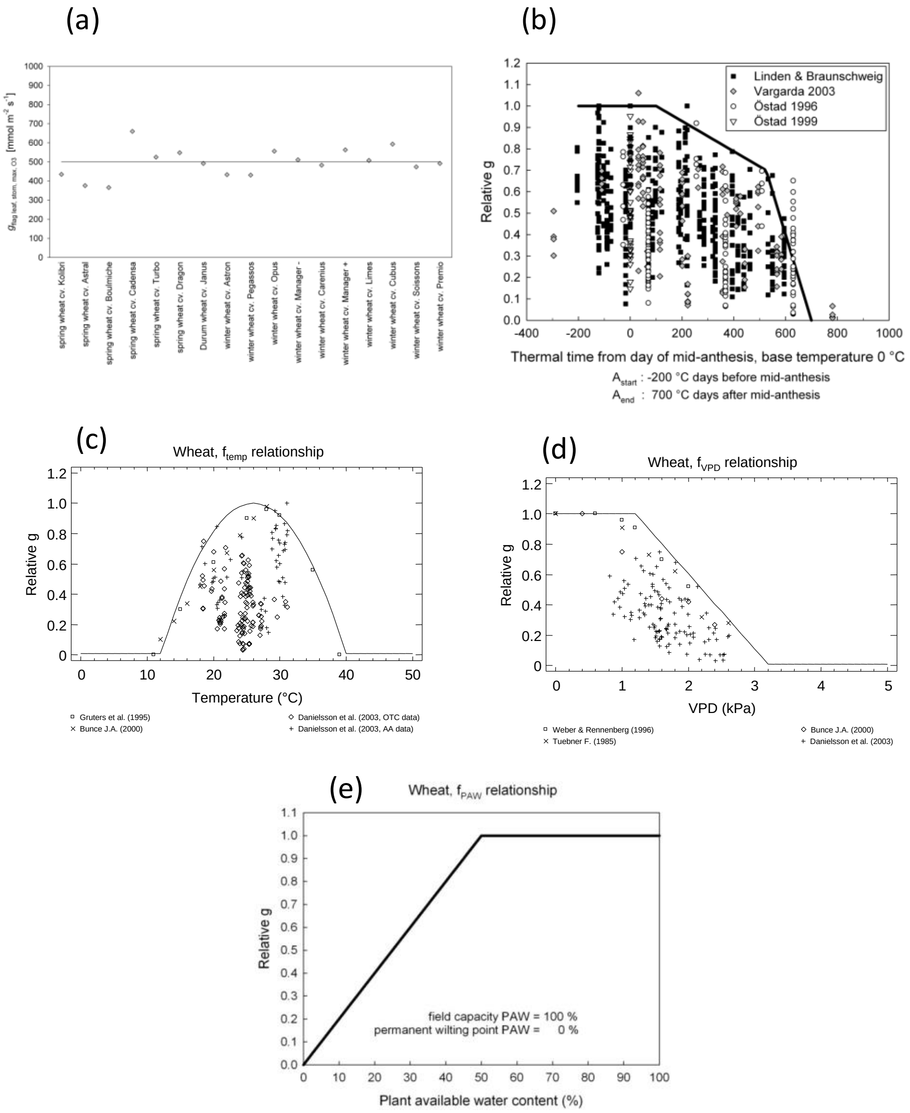
Impacts on the provision of ecosystem services are estimated on the basis of the difference between ozone flux or nitrogen deposition under each scenario and an assumed baseline. Two reference points – 1987 and 2007 – are used to specify a constant baseline level of concentrations

Box 3.1. Calculating the stomatal flux of ozone

Stomatal flux of ozone for an upper canopy sun-lit leaf is modelled using a multiplicative algorithm adapted from Emberson et al. (2000a) that incorporates the effects of air temperature (f_{temp}), vapour pressure deficit of the air surrounding the leaves (f_{VPD}), light (f_{light}), soil water potential (f_{SWP}) or plant available water content (f_{PAW}), plant phenology (f_{phen}) and ozone concentration (f_{ozone}) on the maximum stomatal conductance (g_{max}, mmol O_3 m^{-2} projected leaf area (PLA) s^{-1}), i.e. the stomatal conductance under optimal conditions (see figures). The algorithm has the following formulation:

$$g_{sto} = g_{max} * [\min(f_{phen}, f_{O3})] * f_{light} * \max\{f_{min}, (f_{temp} * f_{VPD} * f_{SWP})\}$$

where g_{sto} is the actual stomatal conductance of ozone (mmol O_3 m^{-2} PLA s^{-1}). The parameters f_{phen}, f_{O3}, f_{light}, f_{temp}, f_{VPD} and f_{SWP} or f_{PAW} are all expressed in relative terms (i.e. they take values between 0 and 1 as a proportion of g_{max}), with f_{PAW} replacing f_{SWP} for wheat only, see figures below. Stomatal flux of ozone is estimated at the leaf level using the DO_3SE model (Deposition of Ozone for Stomatal Exchange) which is available in downloadable form at http://sei-international.org/do3se. The DO_3SE model estimates stomatal ozone flux as a function of the ozone concentration at the leaf boundary layer, the transfer of ozone across this boundary layer, stomatal conductance to ozone (g_{sto}) and ozone deposition to the leaf cuticle. Further details of the algorithms used in this calculation can be found in LRTAP Convention (2010).



The flux parameterisation for wheat: (a) derivation of g_{max}, the maximum stomatal conductance; (b) f_{phen}, the effect of phenology on relative stomatal conductance (g); (c) f_{temp}, the effect of temperature on relative g; (d) f_{VPD}, the effect of vapour pressure deficit on relative g; (e) f_{PAW}, the effect of plant available water in the soil on relative g (LRTAP Convention, 2010).

over time for each scenario, with the difference in ozone flux or nitrogen deposition in each year compared with that of the reference year used to calculate impact. The scenario durations differ slightly from those used in Jones et al. (2012). Here we use 2007 as the endpoint of the historical emissions scenario and as the reference year for the future emissions scenario, rather than 2005 in the earlier study. These differences are discussed further in section 3.7.8.

The formulation of the historical and future air pollution scenarios essentially sets out two 'what if' questions for air quality policy, in the context of rising background ozone concentrations and falling nitrogen deposition: (i) in retrospect, what has been the impact on ecosystem service value of changes in these pollutants since 1987; and (ii) looking forward, what will be the expected impact on ecosystem service values under forecast further changes in these pollutants. The historical scenario was only run for GB. Subsequent data processing during work on the damage cost calculations allowed the future scenario to be calculated for the whole UK.

3.2.4 Data used

Ozone data

Due to the choice of the flux method for quantifying impact and availability from previous studies of modelled ozone flux for the UK, it was only possible to run the future scenario for ozone. Ozone and crop data were available to run the analysis for the United Kingdom.

The future scenario comparison used spatially explicit ozone flux (POD_6) at 10x10 km produced by AEA using the OSRM V26c model. Ozone flux data were available for three individual years: 2006, 2007 and 2008. Projections for 2020 were also available from an earlier study (Jones et al. 2013) based on the DECC UEP43 CCC energy projection (see details in Table 2 below), produced by AEA using 2007 as a base year for the climatology. Since the spatial pattern of ozone in 2007 was rather atypical, it was decided to use an average of the three years 2006-2008 to produce a more typical spatial pattern as the reference flux. A regression relationship was used to scale the differences in flux due to changing precursor emissions for the period 2007-2020, based on the reference condition of average spatial pattern in flux over the years 2006-2008 (see Section 3.5). Ozone fluxes for each 10x10 km grid cell were scaled linearly between fluxes in the start year and the end year of the scenario comparison. Figure 1 shows the spatial distribution of ozone flux used in the start and end time periods, and the change between them. Figure 1 shows the highest ozone fluxes in "2007" (represented by the mean of 2006 – 2007) in East Anglia, south west England and north east England, and eastern Scotland. These areas of highest ozone flux coincide with the main wheat growing areas of the UK. The projections to 2020 show a similar pattern, but with higher fluxes. The difference between the time points shows that areas with high flux generally increased by more than areas with low flux.

Table 2. Input data used in the OSRM model to calculate AEA data for 2007, 2020.

Model year	2007	2020
Meteorological data	2007	2007
UK Emissions	2006 NAEI adjusted to 2007	2009 NAEI adjusted to 2020 based on DECC UEP43 CCC energy projection. Spatial distribution of emissions based on NAEI2008 maps
European emissions	2004 EMEP inventory scaled to 2007	EMEP 2008 inventory projected to 2020 using 1) the UNECE PRIMES REF2010 projections, where available and 2) EMEP2008 projections
OSRM version	v23	V26c

Nitrogen data
Nitrogen deposition data were available to run both the historical and future emissions scenarios at 5x5 km resolution across the whole United Kingdom.

CBED deposition data were available as three-year averages for the periods 1986-1988 (as the 1987 reference situation), for 2006-2008 for the 2007 time point and reference year. Deposition for 2020 was calculated using the FRAME model based on projected emissions of oxidised N from the UEP43 energy scenario 3 (Misra et al. 2012); and based on projected emissions of reduced N from Defra report AC0109 (Dragosits et al. Draft) which assumed a decline in agricultural ammonia emissions of 6% from 2008. FRAME outputs were calibrated to CBED deposition in 2008 (Tony Dore pers comm.). We use these deposition data as the basis for analyses in this study. Nitrogen deposition data were scaled linearly between the start and end timepoints of each scenario comparison for each grid cell. Figure 2 and Figure 3 show the spatial distribution of nitrogen deposition used in the start and end time periods, and the change between them, for each scenario. Noteable in the historical scenario is that for some parts of the UK, particularly eastern Scotland and south west England, N deposition increases between 1987 and 2007. However, N deposition decreases across the majority of the UK, except near minor local sources between 2007 and 2020.

3.3 Calculating economic value

Economic analysis used appropriate market price or value transfer evidence described in subsequent sections in more detail for each service. In each scenario year, the difference in value between the scenario and the counterfactual (reference scenario) was calculated. Aggregation of estimated economic values is presented in terms of an equivalent annual value (EAV) for the historic and projected emissions scenarios. The EAV is estimated as:

$$EAV = \frac{PV}{A_{t,r}} \quad [1]$$

Where *PV* is the present value of the change in ecosystem service value and *A* is the relevant annuity factor for time horizon *t* with discount rate *r*. The present value of the change in ecosystem service value is estimated in the standard manner:

$$PV = \sum_{t=0}^{T} \frac{V}{1+r^t} \quad [2]$$

Where *V* denotes the value of the change in ecosystem service provision. Green Book guidance (HM Treasury, 2003) is followed in specifying the discount rate of 3.5%. Calculation of the PV of the change in ecosystem service value provides an estimate of the accumulated damage to ecosystem services from air pollution over the two scenarios, whilst the EAV provides a measure of the annualised change in the value of the flow of ecosystem services for each scenario.

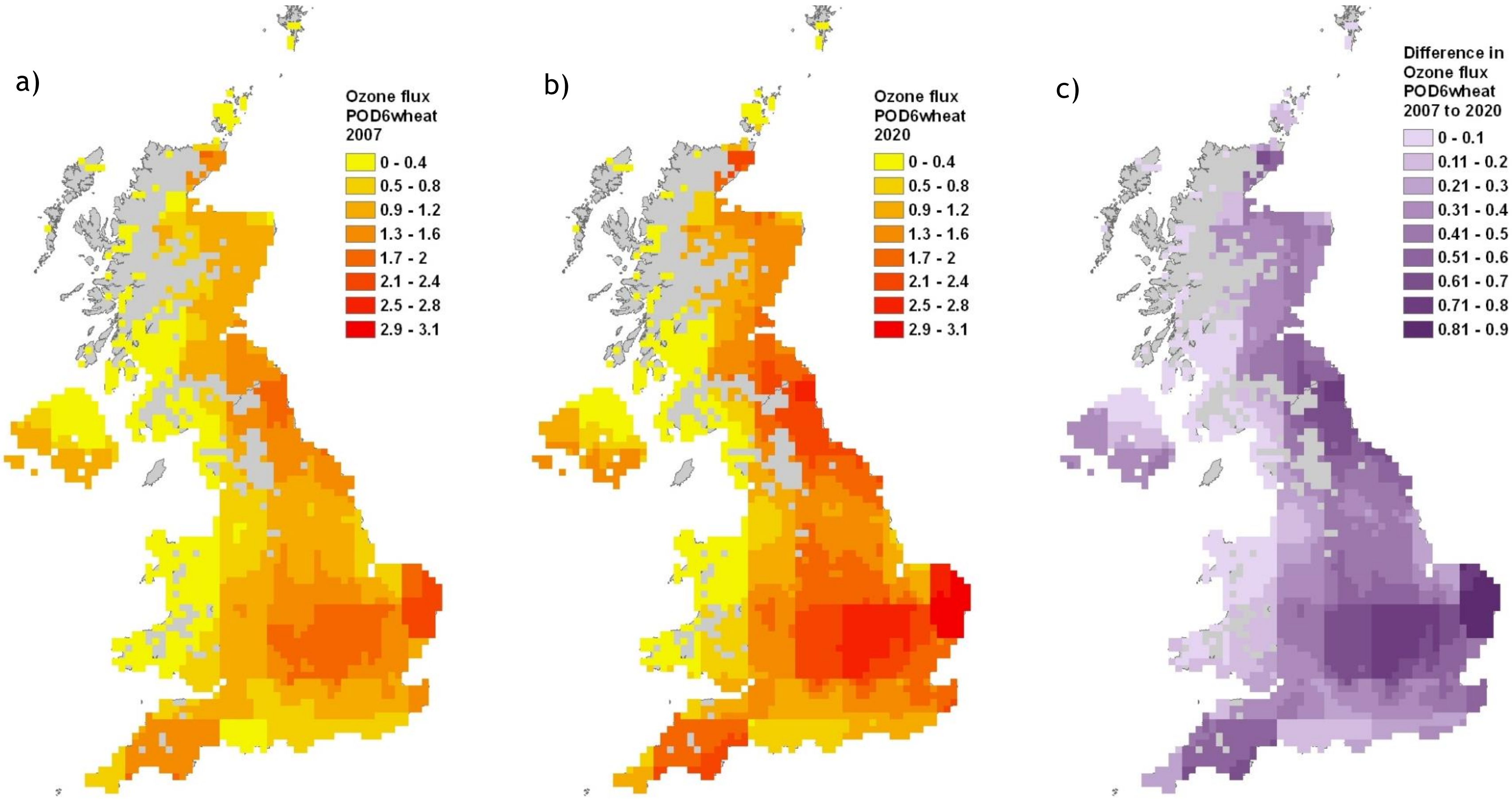


Figure 1. Spatial pattern of ozone flux (POD_6 wheat, mmol m^{-2}) in wheat growing areas used in the future emissions scenario, showing a) 2007 (as a mean of 2006-8), b) 2020, c) Difference between the two timepoints. Data from AEA.

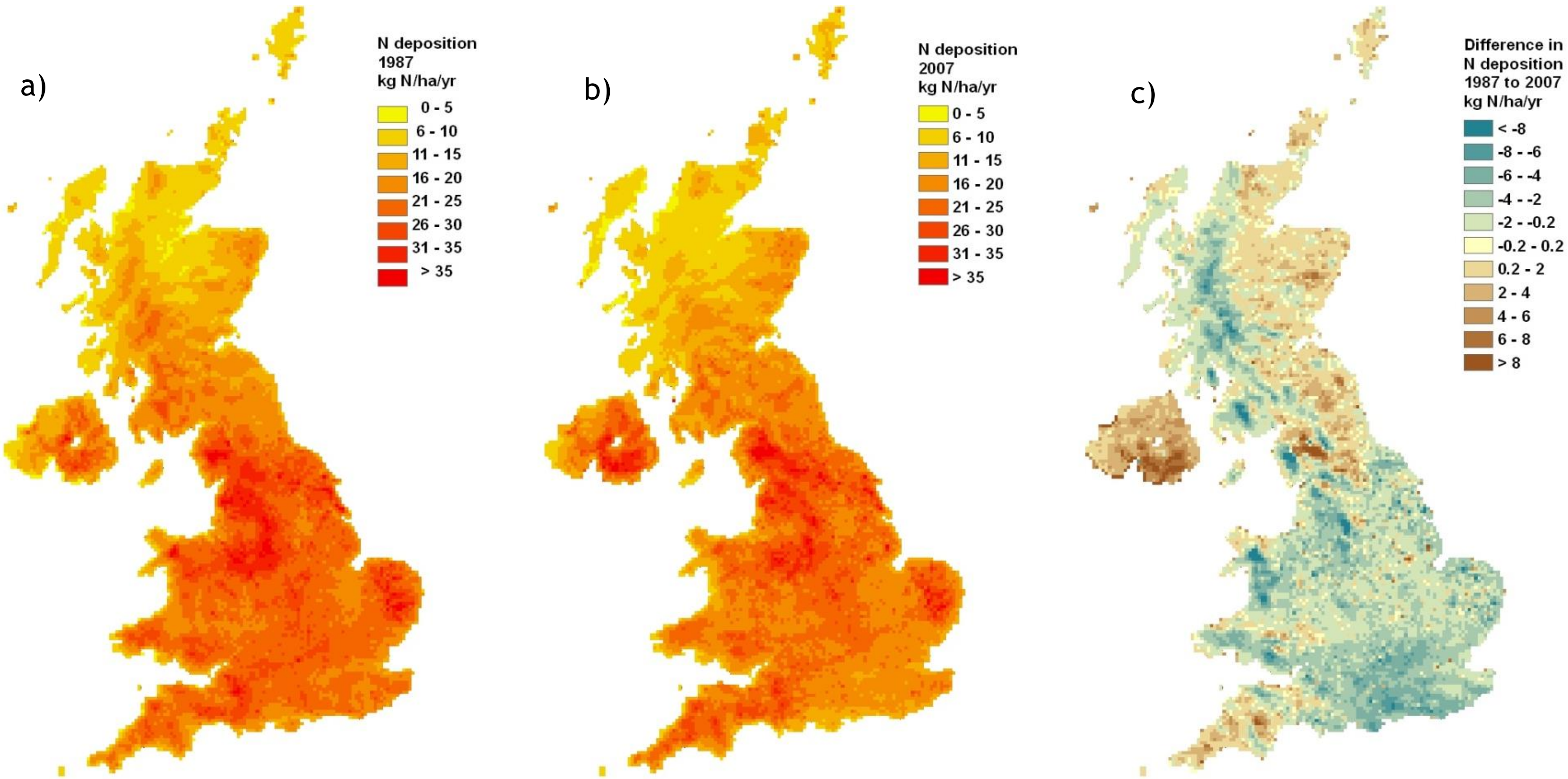


Figure 2. Spatial pattern of nitrogen deposition used in the historical emissions scenario, showing a) 1987, b) 2007, c) Difference between the two timepoints. Data from CBED deposition, kg N ha^{-1} yr^{-1}.

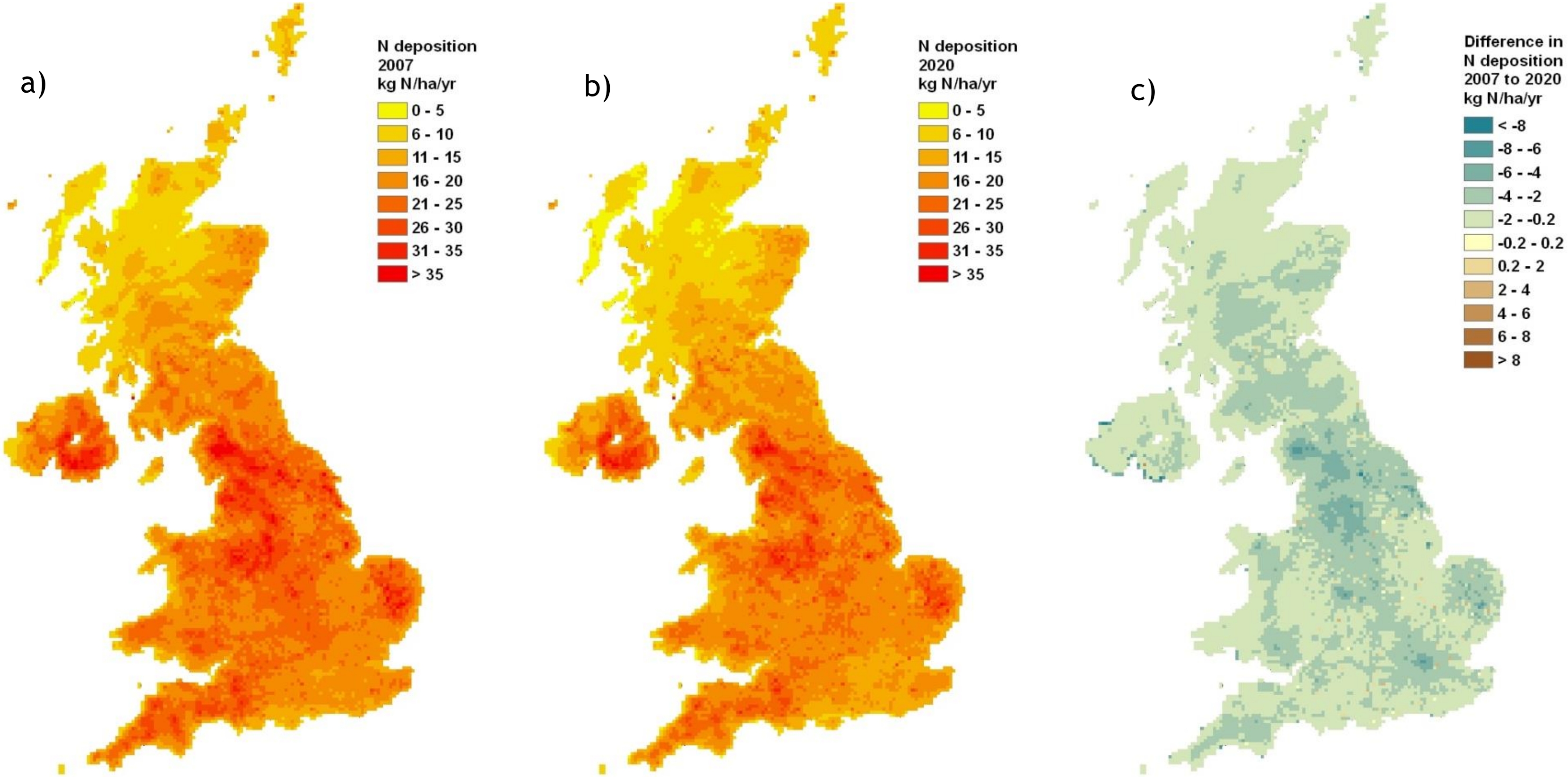


Figure 3. Spatial pattern of nitrogen deposition used in the future emissions scenario, showing a) 2007, b) 2020, c) Difference between the two timepoints. 2007 CBED data; 2020 data from FRAME model, calibrated to CBED deposition in 2008, kg N ha^{-1} yr^{-1}.

3.4 Uncertainty analysis and spatial sensitivity

3.4.1 Method overview

Uncertainty analysis for each step of the impact pathway in the valuation was conducted following the Monte Carlo based approach used in the review of Defra's Air Quality Strategy (IGCB, 2007). This proceeds as follows:

1. Define the scope of the analysis, to demonstrate precisely what has and has not been quantified.
2. Identify the stages of the analysis.
3. Describe the data inputs to each stage.
4. Describe uncertainties, providing numeric ranges where appropriate.
5. Consider how these ranges can be combined.

When describing numeric ranges for uncertainty the following require attention:

- Quantification of the range.
- Statement of what the range represents (e.g. absolute limits or confidence interval).
- Distribution of values within the range. The following have been considered here:
  - Uniform, where all values within the range are equally likely.
  - Triangular, where values towards the centre are more likely than those closer to the extremes.
  - Normal, similar to triangular in effect, but used where it is possible to base the range on statistical evidence.
- Whether uncertainties in parameters are independent of each other.

The uncertainties through the analytical chain can then be combined, for example using Monte Carlo analysis to define an overall range and distribution within that range.

There is potential for extreme results to appear when combining a large number of ranges in a single Monte Carlo run (e.g. when sampling selects high values for every parameter) to derive an estimate of pollution impact. This is an obvious problem with sensitivity analysis when applied to a large number of variables simultaneously. However, over a full set of Monte Carlo runs, results will demonstrate that such a situation is very unlikely. It is much more likely in any run that values for some parameters will be lower than the best estimate and some will be higher, with errors then cancelling out to a significant degree, constraining the overall range.

The derivation of range is difficult for some parameters because of limited availability of data. In such cases it is appropriate to apply a range based on expert judgement rather than not to apply any range at all. There is opportunity to challenge any judgement made provided that the analysis is performed transparently.

This process may seem overly complex simply for describing the variability around best estimates (deterministic calculations) that can otherwise be quantified. However, this overlooks the following points:

1. Where probability distributions for one or more variables are asymmetric around the best estimate, the use of best estimates can provide a misleading indication of overall impacts;

2. It provides a mechanism for treating uncertainty in a uniform way across a set of inputs generated by experts in different disciplines (pollution modelling, impact assessment, ecology, health, etc.);
3. The process enables identification of the factors that contribute most to uncertainty;

The final results account for uncertainty in a large number of variables in terms of a best estimate and range defined in terms of % confidence limits.

3.4.2 Spatial sensitivity

Sensitivity to the issues identified above only partially accounts for uncertainty in the methods defined for each receptor. Another source of uncertainty is the spatial context of pollutant depositions and fluxes, and the exposure of different receptors to pollution.

A major focus of this study was to conduct calculations of ozone impact on a spatially explicit basis, taking into account spatial variation in ozone flux, and spatial variation in the receptors, which together define actual exposure of receptors to ozone more realistically than the previous study which used UK average values in a proof of concept approach (Jones et al. 2012).

3.4.3 Uncertainty analysis in a spatial context

The impacts of air pollutants are calculated from models that depend on estimates of ozone flux or nitrogen deposition, amongst other variables. These variables are uncertain and so are the model parameters. We used Monte Carlo simulation to propagate the uncertainty in the parameters and variables through the model, thereby calculating the uncertainty in the estimated impacts of ozone. To do our Monte Carlo simulations, we sought probability density functions (PDFs) to describe the uncertainties in the model parameters and variables. We assumed that the uncertainties in the model parameters were at the UK scale (i.e. for any one iteration of the Monte Carlo simulation the same values of the model parameters were applied in each grid cell). For the model variables, unless otherwise stated, the uncertainties were applied at the scale of a grid cell and assumed to be independent. We scaled the uncertainty so that at UK scale the errors were proportional to those we would expect given assumptions that the errors were independent. We used @Risk software (Palisade Corporation, USA, 2010) to run the Monte Carlo simulation. We used Latin hypercube sampling and ran the simulation for 10 000 iterations.

3.5 Calculation of damage costs

3.5.1 Ozone

Marginal damage costs were calculated for the impact of ozone on crops, i.e. the cost per unit change in ozone flux (POD_6wheat). Damage costs were calculated as follows:

For ozone, the costs or benefits of changes in pollution were calculated as Equivalent Annual Value. Equivalent Annual Value was then divided by the average difference in ozone flux between years for each scenario, to give the damage cost. In this spatial analysis, the average difference in ozone flux over each of the scenario periods was calculated separately for each 10x10km grid cell in the UK, and then averaged to UK level. The UK average flux for start and end years and the average difference in ozone flux used to calculate damage cost for the future scenario are shown in Table 3 below.

Ozone concentrations and therefore flux in the UK are a function of both precursor compounds emitted in the UK and precursor compounds imported into the UK atmosphere as a result of long-range transport, which are subsequently affected by a range of atmospheric chemical transformations

(ROTAP, 2012). Separately attributing changes in ozone flux to emissions of individual source compounds is beyond the scope of this study and requires further research work. Therefore, marginal damage costs are presented in terms of changes in UK ozone flux for wheat using the POD_6 metric.

Table 3. UK average ozone flux (Wheat POD_6, mmol m^{-2}) in 2007 (calculated as the mean of 2006, 2007 and 2008), 2020 and the spatially calculated difference between them, used to calculate damage flux, calculated for the 10 x 10 km grid squares where wheat is grown.

Future scenario (using AEA data, 10x10 km)		
Average 2007	Average 2020	Average difference
0.9073	1.2770	0.1849

3.5.2 Nitrogen

For nitrogen, damage costs for Appreciation of Biodiversity were only calculated for the Future emissions scenario. This entailed separate calculations of impact for ammonia and for nitrogen oxides. Following discussion with nitrogen impact experts it was decided that the most appropriate methodology was as follows: In the absence of specific dose-response relationships for reduced forms of N and for oxidised forms of N, and in the absence of consensus on whether oxidised or reduced N is more damaging to plant species richness it was assumed that they have equal impact per unit of N deposited. The dose response functions are based on total N deposition, and separate oxidised or reduced N deposition cannot simply be substituted into the equation. Therefore the total impact in each year was calculated using total N deposition, and the value apportioned to oxidised or reduced N according to the proportion of change in the deposition of each N form. i.e. If total deposition reduced by 2 kg N ha^{-1} yr^{-1} and 25% of this change (i.e. 0.5 kg N ha^{-1} yr^{-1}) was due to a change in deposition of reduced forms of N, then 25% of the value was apportioned to reduced N, and 75% to reductions in oxidised N. In practice the proportions of change due to reduced N were much lower since deposition of reduced N changed little over the future emissions scenario period.

The resulting EAV was divided by the average change in oxidised N emissions and in ammonia emissions used in the deposition modelling within the FRAME model (Table 4).

Table 4. Change in emissions of NO2 and NH3 used to calculate damage costs for the future scenario. Emissions are scaled linearly between start and end years of the scenario.

	NO_x as NO_2		NH_3	
Year	NO_2 Emissions (kt)	Change relative to baseline	NH_3 Emissions (kt)	Change relative to baseline
2007	1403.0	0.0	289.6	0.0
2008	1363.1	-39.9	288.2	-1.4
2009	1323.1	-79.9	286.9	-2.7
2010	1283.2	-119.8	285.5	-4.1
2011	1243.3	-159.7	284.2	-5.5
2012	1203.3	-199.7	282.8	-6.8
2013	1163.4	-239.6	281.4	-8.2

2014	1123.5	-279.5	280.1	-9.5
2015	1083.5	-319.5	278.7	-10.9
2016	1043.6	-359.4	277.3	-12.3
2017	1003.7	-399.3	276.0	-13.6
2018	963.8	-439.2	274.6	-15.0
2019	923.8	-479.2	273.2	-16.4
2020	883.9	-519.1	271.9	-17.7
Average change (kt)[1]		279.521		-9.546

[1] Not including Reference Year.

3.6 Valuing the impact of ozone on wheat production in the UK

This section reports on the valuation of ozone on wheat production in the UK.

3.6.1 Summary

- Wheat is one of the most ozone-sensitive crops, and this study confirms previous investigations (Mills et al., 2011, Mills and Harmens, 2011) showing that ozone affects yield of wheat in the UK
- Impacts on wheat yield were assessed using the ozone flux metric specific to wheat, POD_6
- Under a future ozone scenario, the loss of production due to ozone replicates the spatial pattern of current wheat production with ozone fluxes being highest in those areas where wheat is extensively grown.
- There was a net cost to wheat production due to increases in ozone of -£18.6 million EAV (-£22.0m to -£15.4m, 95% CI) for the future scenario.
- The damage cost per unit ozone flux of POD_6wheat is -£100.6 million EAV (-£119.0m to -£83.4m, 95% CI) for the future scenario.
- The key assumptions in this study were: The areas where wheat is grown, and determinants of yield other than ozone do not change between 2007 and 2020; The response function for wheat is applicable to current UK cultivars; The price of the UK wheat crop will remain the same between 2007 and 2020, subject to discounting; The three years used in the study (2006, 2007 and 2008) are representative years for current ozone flux; The future scenario used assumes compliance with existing legislation by 2020 and effects of climate change were not included; The spatial variation in ozone flux does not change between 2007 and 2020; The OSRM-SOFM model is equally accurate for all years and can accurately model ozone fluxes at/close to the threshold for flux accumulation (Y=6 nmol m^{-2} s^{-1}).
- Recommendations for further work include for wheat: New field-based ozone experiments with current cultivars; Testing of flux model parameterisation with current UK cultivars; Inclusion of projections of effects of climate change on wheat areas, wheat production, and ozone concentration and flux in the calculations; Expanding the range of years for which ozone flux is calculated to five for both the current and future scenarios; Consideration of use of other models available for the UK for ozone flux, including the Eulerian EMEP4UK model adapted for the UK from the EMEP model being used by the LRTAP Convention. Flux-based response functions and spatial data for ozone flux and yield are already available for potato and oilseed rape and could be applied to an economic evaluation using the method described for wheat. Improvements in their application could be made as indicated for wheat, and new experiments for other crops could be conducted to facilitate development of flux-effect relationships.

3.6.2 Definition of the policy good and affected population

Overall, wheat is the most important agricultural crop in the UK and is grown on approximately 2 million ha each year. Wheat grain is milled for flour for use in bread, biscuit and cake making as well as for animal feed and industrial uses (including bio-ethanol and starch production, Francis, 2009). The annual value of the wheat crop for the UK economy is £1 - 2 billion (UK national statistics[4]), with variation reflecting the volatility of the global wheat grain market.

3.6.3 Change in provision of the policy good

3.6.3.1 Baseline

Average farm gate prices for milling wheat (£ per tonne) in recent years were: £76 (2005 and 2006), £109 (2007), £152 (2008), £122 (2009 and 2010) and £175 (2011).

3.6.3.2 Impact pathway

Summary of approach

Ozone effects on wheat were valued by:

- Use of yield and wheat area data per 10 x 10 km grid square for 2006 and 2008 collated for the Mills et al. (2011) study. Mean values per grid square were used for the current study.

- Determining the ozone flux for 2006, 2007, 2008 and 2020 using the Surface Ozone Flux Model (SOFM) and Ozone Source Receptor Model (OSRM) at 10 km x10 km resolution for wheat (data provided by Defra projects AQ0816 (ICP Vegetation) and AQ0815 (O3 umbrella). The OSRM model calculates hourly ozone concentrations at receptor locations throughout the United Kingdom. The SOFM evaluates the components of resistance that control the rate of deposition of ozone to vegetation. The SOFM postprocessor then combines the OSRM output (or measured ozone concentrations) with the SOFM resistance values to provide estimates of the accumulated flux of ozone deposited from the atmosphere to surface vegetation during the growing season. The accumulated flux metrics correspond to the metrics specified in the 2010 version of the LRTAP Convention Modelling and Mapping Manual. Due to the inter-annual spatial variation in ozone flux in the UK, the mean value per grid square for 2006, 07 and 08 was used to represent the current year (2007). The grid square POD6 values for 2020 were then calculated by applying a conversion function derived by a regression of 2007 against 2020 values (2020 = 1.4075 *2007, r^2 = 0.97) to the 2006, 2007, 2008 mean values.

- Calculating the effect on yield using the POD_6-effect relationship in the LRTAP Convention's Modelling and Mapping Manual, reproduced in Figure 4. This function has been derived from field-based open-top chamber experiments conducted in Belgium, Finland, Italy and Sweden using five cultivars of wheat. Full details of the approach are provided in Appendix B.

[4] https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom

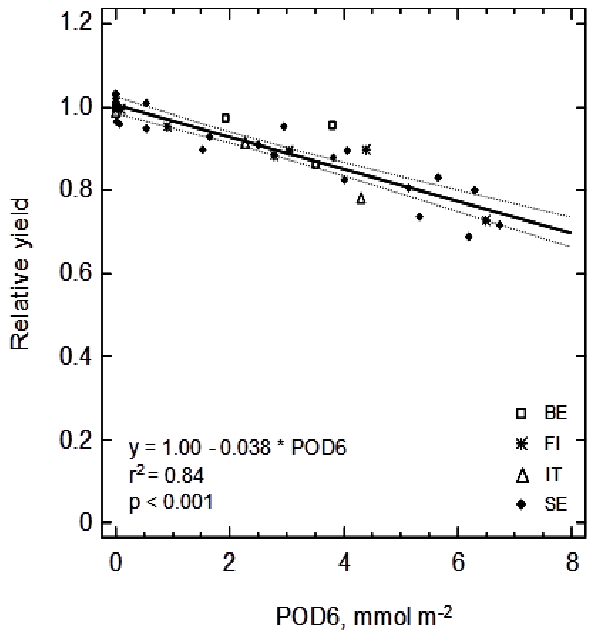


Figure 4. Response function for the effects of ozone on wheat yield derived using the flux-based methodology (POD_6). This response function can be found in the LRTAP Convention's Modelling and Mapping Manual and in Grünhage et al. (2012).

Changes in wheat production in the UK due to ozone

Figure 5 shows wheat production in the UK, under current ozone conditions (= mean of 2006 - 2008, considered the "reference year" for the future scenario). This shows a focus in central and eastern England, and including eastern Scotland. The optimum climatic and soil conditions for wheat production in the UK are largely coincident with the areas with highest ozone flux. Thus, under a future ozone scenario, the loss of production due to ozone replicates this pattern, largely as production in a grid square is dominated by the area of wheat in that square.

3.6.4 Selection of value transfer evidence

Calculation of economic loss used the five-year average farm gate wheat value, centred on 2007 (£109/tonne).

3.6.5 Application of value transfer

Impacts of ozone on wheat production were calculated using the spatially explicit change in yield and therefore production, coupled with the value transfer evidence, subject to 3.5% discount rate. These calculations were then subject to uncertainty analysis to produce the final estimated value, see Section 3.6.6.

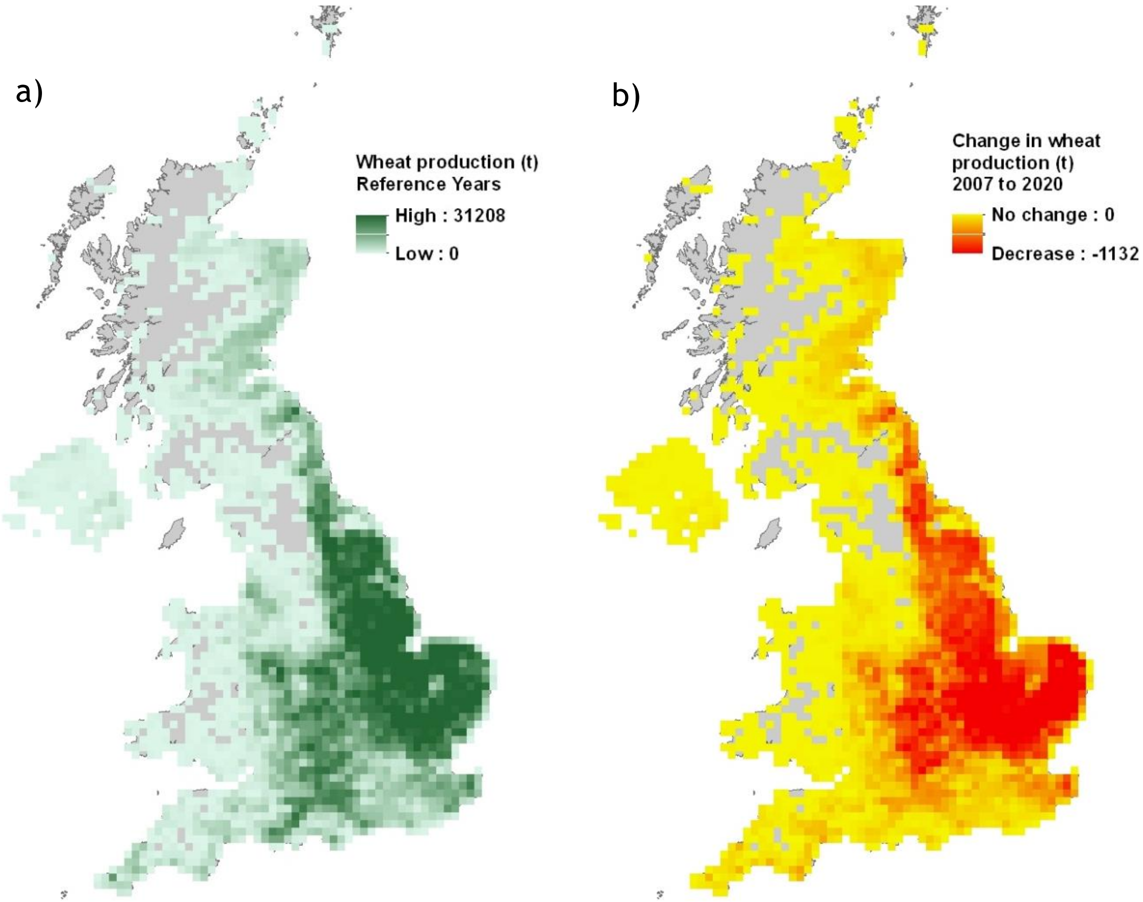


Figure 5. Ozone impacts on wheat production in the future scenario showing a) Wheat production (t per 10 x10 km square) in the reference situation 2007 and b) Difference in wheat production (t per 10 x10 km square) due to ozone in 2020.

3.6.6 *Results and damage costs, including 95% Confidence Intervals*

The variables in the model for which we assigned an uncertainty are listed in Table 5, along with the assumptions made. Discount factors and the price of wheat did not have an uncertainty associated with them. Results of the uncertainty analysis are shown in Table 6. For uncertainty analysis of ozone on wheat, we suggest to use the mean and 95% Confidence Intervals since the uncertainty distributions are normal. The results of the deterministic calculations are shown in Appendix B.

The estimated cost to wheat production due to increasing ozone is -£18.6 million EAV (-£22.0m to -£15.4m, 95% CI) for the future scenario.

The damage cost per unit increase in ozone flux of POD_6wheat is -£100.6 million EAV (-£119.0m to -£83.4m, 95% CI) for the future scenario.

Table 5. Assumptions and parameterisation for uncertainty analysis of ozone impacts on wheat.

Variable	Assumptions and parameterisation
Spatially variable ozone flux (POD_6)	We assumed that the uncertainty for each predicted value of ozone was distributed normally with 95% limits of ±20%. This was based on Klingberg et al. (2008) who estimate the uncertainty in ozone flux predicted from model based concentrations of ozone and weather variables compared with those predicted from observed data. Our estimate of uncertainty does not account for the uncertainty in predicting climates into the future.
Wheat production	Based on the information from the UK greenhouse gas inventory we assumed the uncertainty in the crop production across the UK was distributed normally with standard deviation 0.7% of the mean.
Parameters for the equation to predict Relative yield loss.	The model to predict relative yield loss was derived by fitting a linear regression equation to data; therefore we assumed that the uncertainty in both model parameters was distributed normally. The constant parameter has mean 1 and standard deviation 0.01, and the slope parameter has mean -0.038 and standard deviation 0.003.

Table 6. Results from uncertainty calculations: Ozone impacts on wheat production, rounded to nearest £1,000.

	Future scenario: Reference year 2007, to 2020 (based on UEP43 scenario)		
	Net Present Value of Benefits (2007 to 2020)	**Equivalent Annual Net Benefit**	**Damage Cost, per unit ozone flux POD_6wheat**
Mean	-£191,508,000	-£18,588,000	-£100,555,000
Standard deviation	£17,142,000	£1,664,000	£9,001,000
Min	-£258,083,000	-£25,050,000	-£135,511,000
Max	-£128,448,000	-£12,467,000	-£67,444,000
2.5 percentile	-£226,580,000	-£21,992,000	-£118,970,000
97.5 percentile	-£158,876,000	-£15,421,000	-£83,421,000

3.6.7 Discussion of results

In this study we used the most up to date method for quantifying ozone effect – ozone flux. This approach takes into account the modifying effects of varying temperature, humidity, light and soil moisture as well as plant growth stage on the total amount of ozone taken up by the plant, and is much more biologically relevant than methods based on ozone concentration above the plant. As both ozone concentration and the climatic conditions influencing ozone uptake vary spatially both within and between years, we used the mean value per grid square for three years (2006, 2007, 2008) as the base year. Within the scope of this project, there was insufficient resource to generate additional data required to use five years of ozone data as recommended in the LRTAP Convention Modelling and Mapping Manual.

The marginal cost approach used for valuing effects on crop yield for this study differs from the approach used by the LRTAP Convention where effects of ozone in a single year (or averaged over several years) are calculated relative to pre-industrial ozone concentrations, represented by zero ozone flux (Mills et al., 2011, Mills and Harmens, 2011). Such an approach provides an absolute value for the economic loss for a given ozone year or scenario, whereas in the current study to align with other economic valuations of marginal effects of air pollutants on ecosystem services in the UK for use in policy appraisal, the difference in economic losses between two years (2007 and 2020) was used to determine the annual equivalent value of loss after applying a discount factor and an assumed linear increase in ozone between the two years. Using the same modelled flux data for wheat used in this study for 2007 (averaged for 2006, 07, 08) and 2020, the absolute values for losses are provided for comparison in Table 7. The annual absolute economic loss relative to zero ozone flux calculated for ozone in the two years was 4.5 and 6.5 times higher at -£84.6 million and -£122 million for 2007 and 2020 respectively than the marginal cost (as Equivalent Annual Value) determined in the current study (-£18.6 million EAV, Table 6). Thus, the marginal costs approach is taking into account the difference between 4.85% (2020 yield losses) and 3.45% (2007 yield losses), without valuing the 3.45% losses already happening (relative to zero POD6).

Table 7. Calculation of absolute losses in yield for wheat for 2007 and 2020, relative to zero flux (POD_6 = 0 mmol m^{-2}) of ozone, following methodology used in LRTAP convention.

	2007 (mean of 2006, 07, 08)	**2020**
% loss in yield, based on response function	3.45	4.85
Losses in production (million tonnes of wheat grain)	0.79	1.14
Total loss in value (£)	£84,690,000	£121,997,000
Mean ozone flux (POD_6, mmol m^{-2})	0.91	1.28
Cost per unit ozone flux (POD_6 wheat)[1,2]	£93,347,000	£95,536,000

[1] Calculated from the total loss in value and mean ozone flux
[2] Method assumes a step change in ozone, not calculated over time, and not discounted.

In policy terms, use of reference to zero ozone flux (roughly equivalent to pre-industrial ozone concentrations) in crop loss calculations as shown in Table 7 introduces the question over whether zero flux is an achievable target. Potentially a different reference point could be used but this would require further scenario analysis to understand what the minimum achievable ozone flux is based on maximum feasible reductions in precursor emissions within Europe and the northern hemisphere.

Within the scope of the current study it was not possible to validate the economic losses found. However, there are published studies of effects of ozone determined by either quantifying the beneficial effects of air filtration to remove ozone and multi-factor analysis of wheat production data that provide some agreement with the percentage effects found here. For example, Pleijel et al. (2011) analysed data from 30 experiments conducted in 9 countries in North America, Europe and Asia in which wheat was grown in field-based open-top chambers with charcoal filters that reduced ambient ozone by on average 63 % from a daytime mean of 34.6 ppb to 13.2 ppb. The average yield improvement was 9 % and the median was 7 %. Selecting out the data from this study for countries relevant to the UK (10 data points from Belgium, Denmark, Ireland and southern-Sweden), the mean benefit in wheat yield was 5.23 % for a reduction in daytime ambient ozone concentration from 26.6 ppb to 6.9 ppb. This magnitude of effect tallies approximately with the percentage losses calculated for the UK in Table 7. Using a different approach, Kaliakatsou et al (2010) conducted an econometric analysis of data from UK wheat variety trials at 149 sites over a period of 13 years (1992 – 2004) in relation to the concentration parameter, AOT40 which accumulates ozone concentrations above 40 ppb during daylight hours. Their study indicated that ambient ozone caused a mean of 3.7 % loss in wheat yield over the period, with a relatively small (1 %) increase in AOT40 reducing yield by 0.054 %. A multi-factor farm-scale evaluation of ozone effects on profits for farms in England and Wales indicated a 1 % decrease in profits for wheat for every 10 % increase in AOT40 (Neeliah and Shankar, 2010). As AOT40 accumulates ozone concentrations above 40 ppb whilst POD_6 accumulates fluxes at concentrations above 10 -15 ppb, then unit rates of change are not directly comparable with the current study, but the overall 3.7 % loss from the Kaliakatsou et al. (2010) study is within the range expected in this study.

The next stage in this analysis could include an ozone flux-based assessment of how farmers might compensate for detrimental effects of ozone on yield. Such an assessment has been conducted for France using AOT40 as the ozone parameter for 2000 and three 2030 scenarios (Humblot et al (2013). Their comprehensive spatial analysis included effects of ozone on farmer crop choices using models for economic supply, crop production and compensatory N fertilizer application. Humblot et al (2013) predicted that increases in ozone by 2030 would result in a large shift towards production of ozone-resistant barley (14 % increase in total production) in preference to ozone-sensitive wheat (30 % decrease in total production). Taking all of these changes into account, in economic terms, the worst case scenario (2030-SRE) was linked to a decrease in gross margin of 360 million Euro (-1.34 % compared to 2001) whilst for the most realistic scenario losses were more modest at 47 million Euro. Their study also included indirect effects of ozone on greenhouse gas emissions. They found that CH_4 emissions were likely to increase as land-use changed towards animal production as cereal yields fell, however, in CO_2 equivalents this effect was outweighed by variations in N_2O emissions due to changes in fertilizer usage. It would be very beneficial to conduct such an analysis for the UK in order to determine future effects of ozone.

3.6.8 Key assumptions and caveats

- Wheat production and areas grown do not change between 2007 and 2020. However, small changes in area of production are likely, whilst production is highly variable dependant on annual fluctuations in weather.
- The response function for wheat is applicable to current UK cultivars. The function was derived mainly from experiments conducted in the late 1980s and 1990s with cultivars of

wheat that were commonly grown at that time. Grünhage et al. (2012) evaluated the applicability of this function to current cultivars of wheat and found that the key input parameters such as maximum stomatal conductance and relationships for temperature, humidity etc., were comparable to those used to derive the function. Although current UK cultivars may have different sensitivity to ozone (as yet untested), their flux model parameterisation is likely to match that used and thus we conclude that the response function used was the best currently available.

- The economic value of the UK wheat crop will remain the same between 2007 and 2020. In reality, the value varies enormously from year to year, dependant on global as well as European market drivers together with climatic influences. By using a 5 year mean value, centred on 2007, we have included some consideration of this variation. However, with climate change and increasing pressures on food supplies, it is quite likely that the value of wheat will increase between 2007 and 2020, resulting in an increasingly higher effect on annual equivalent and net value during the time period than presented here.

- The three years used in the study (2006, 2007 and 2008) are representative years for current ozone flux. There was spatial variation in ozone flux between the three years, with for example, higher fluxes in NE England in 2006 than in 2008, that were to a certain extent smoothed out by using the three years data. Due to the inter-annual variability in ozone concentrations and fluxes, a longer time run of five years is recommended in the LRTAP Convention's modelling and mapping manual in order to provide a better representation of an average year.

- The future scenario used (DECC UEP43 CCC energy projection and UNECE PRIMES REF2010 projections) assumes compliance with existing legislation by 2020. Quite possibly, this may not be achieved and ozone concentrations will be higher than predicted. Furthermore, effects of changing climate on ozone production in the UK are not included in this scenario and may introduce additional error.

- The flux model used (the OSRM-SOFM) is equally accurate for all years. Previous studies have shown that this model underestimates ozone flux in hot dry conditions, leading to between year variations in accuracy. For example, in 2006 flux calculated from measured values was 1.5 x that modelled by OSRM-SOFM for wheat, whilst in 2008 the correlation was much stronger with measured values being 0.98 x modelled values (Abbot et al., 2011).

- The spatial variation in ozone flux does not change between 2007 and 2020. Although this cannot yet be quantified, with climate change and changes in local, regional and global ozone precursor emissions impacting on the UK, it seems likely that there will be some changes.

- The OSRM-SOFM model can accurately model ozone fluxes at/close to the threshold for flux accumulation (Y=6 nmol m^{-2} s^{-1}). A common concern amongst regional air quality modellers is the uncertainty associated with modelling above a threshold, with uncertainty increasing as the threshold value increases (Simpson et al., 2007). There is strong biological evidence for the need for a threshold, however, as indicated by regression analysis for dose-response functions using a range of thresholds.

3.6.9 Recommendations for further work

For wheat, further improvements in the accuracy of predictions could be made by:

- New field-based ozone experiments with current UK cultivars of wheat
- Testing of flux model parameterisation with current UK cultivars not included in the Grunhage et al. (2012) study.
- Inclusion of projections of effects of climate change on wheat areas, wheat production, and ozone concentration and flux in the calculations
- Expanding the range of years for which ozone flux is calculated to five for both the current and future scenarios
- Consideration of use of other models available for the UK, including the Eulerian EMEP4UK model adapted for the UK from the EMEP model being used by the LRTAP Convention
- Validation of results using an epidemiological analysis of wheat yield data in the UK over the last two decades and/or further ozone exposure experiments using current varieties

For other crops:

- Flux-based response functions and spatial data for ozone flux and yield are already available for potato and oilseed rape and could be applied to an economic evaluation using the method described for wheat. Improvements in their application could be made as indicated for wheat.

For all crops:

- Conduct a comprehensive economic analysis of future effects of ozone on crop production in the UK, taking into account effects on farmer crop choice and fertilizer usage.
- Further discussion is needed on how to calculate damage costs for ozone as a secondary pollutant. Although ozone flux is the most scientifically accurate method currently available for valuation of effects related to vegetation, the possibility of using other ozone metrics, or relating damage directly to emissions of precursor chemicals could be explored.
- In order to calculate flux-based damage costs for ozone in new policy situations, the relevant flux-based measures (e.g. POD_6wheat) need to be calculated for each scenario.

3.7 Valuing the impact of nitrogen on biodiversity

This section reports on the valuation of nitrogen impacts on appreciation of biodiversity in the UK.

3.7.1 Summary

- Nitrogen affects plant species richness in a large number of UK habitats, including acid grassland, sand dune grassland, mixed grassland, heaths, bogs, deciduous woodland.
- Based on a previous study, dose-response relationships were derived for nitrogen deposition on species richness for four of these habitats: heathland, acid grassland, sand dune grassland and bogs. Details of the equations can be found in Appendix C.
- Spatially explicit calculations were made for individual grid cells at 5 x 5km resolution. For each of the four habitats, in each grid cell, in each year, expected species richness was calculated based on the N deposition for that cell.
- Percentage difference in species richness from the reference year for that scenario was then calculated.
- Value transfer evidence for changes in species richness utilised Willingness To Pay (WTP) values for maintaining or increasing populations of non-charismatic species (plants, insects, other invertebrates) from a Choice Experiment (Christie and Rayment, 2012). Values were scaled according to the proportional change in species richness in each habitat. WTP values for charismatic species (animals, birds, butterflies) are a factor of 5 greater than for non-charismatic species, but impacts cannot currently be modelled. There is evidence of N impacts on some charismatic species, therefore this remains a major gap in the valuation assessment. This illustrates the importance of developing dose-response functions for these species.
- Declines in N deposition resulted in a combined benefit for appreciation of biodiversity in the four habitats with a mean Equivalent Annual Value (EAV) of £32.7m (£4.5m to £106.2m, 95% CI) in the future scenario, with the greatest increases in value occurring for heathland and for acid grassland. Uncertainty analysis was not run for the historical scenario, but the deterministic mean EAV was £14.9m.
- Key assumptions are that: changes in species richness due to N are independent of climate, other pollutants and site-specific effects; linking WTP directly to changes in species richness represents an improvement in the methodology, but still holds large assumptions; changes in N deposition cause immediate change in species richness, without lags – in practice lags will occur and recovery may not happen at all.
- Recommendations for further work include: Develop dose response functions for charismatic species; further refinement of the dose response relationships for non-charismatic species could be undertaken, including response functions for other habitats such as broad-leaved woodland and neutral grasslands; conduct specific valuation studies for assessing air pollution impacts on biodiversity.

3.7.2 Definition of the policy good and affected population

As noted in Jones et al. (2012), 'appreciation of biodiversity' remains a poorly-defined good. Under the UN Convention on Biological Diversity, biodiversity is formally defined as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*" (Article 2, p.5; CBD, 1992). Given the highly interactive and co-dependent role that biodiversity has across different habitat types and consequently on the provision of ecosystem services, the 'value' of biodiversity per se can be challenging to coherently assess. Abson et al. (2011) take the approach of considering the value of biodiversity (conservation) in terms of use and non-use values, with the use value component is further split into: (i) the role of biodiversity in the direct delivery of ecosystem services; and (ii) the role of biodiversity in underpinning ecosystem service delivery.

The role of biodiversity in the direct delivery of ecosystem services influences the provision of a number of intermediate and final ecosystem services and goods; for example pollination, fertilisation and pest reduction effects (e.g. on food production); maintaining genetic diversity and bioprospecting; and (biodiversity-related) recreation. From a practical perspective however, the contribution of biodiversity can be assumed to be captured in the valuation of the final goods (e.g. recreation and aesthetic values for uses involving watching wildlife, and provisioning or regulating services for other direct or indirect uses of biodiversity); hence a separate attempt to value the contribution of biodiversity would introduce an element of double-counting.

With respect to the role of biodiversity in underpinning ecosystem service delivery, a precursor for valuation is the need to understand how biodiversity is related to the primary structure of ecosystems and the composition that is required to ensure its healthy functioning, the resilience of ecosystems to respond to external shocks (i.e. how does species richness allow systems to recover), and the insurance function that biodiversity provides within systems (i.e. a greater range of species ensures that some ecological functions will continue if other fail). Here it can also be argued that separately valuing the supporting and intermediate functions of biodiversity entails a significant risk of double-counting, since – conceptually at least – this is again accounted for in the final services supported by biodiversity. However some caution is required since it must be recognised that value estimates for the supported goods and services will only be accurate if in fact the biodiversity necessary for their provision is maintained in the future. In other words, if a decline in biodiversity is expected - i.e. a depletion in stock – it will be necessary to account for the implications for the value of final services supported by biodiversity. This then raises issues that are beyond the scope of this report in terms of critical levels of natural capital and whether the scientific basis for understanding the implications of biodiversity losses in this regard is presently available.

In terms of non-use values, based on altruistic, bequest and existence motivations, a number of recent studies document the general preference of individuals for the conservation and enhancement of biodiversity (e.g. Morse-Jones et al., 2010; Christie et al., 2006; MacMillan et al., 2006). This provides the basis for the approach in this study, which defines the 'appreciation of biodiversity' in terms of non-use values associated with conserving elements of the natural environment, plant and animal species.

3.7.3 Change in provision of the policy good

3.7.3.1 Baseline

Biodiversity is often measured using convenient proxies such as plant species richness, for which there is considerable UK data, including from large-scale national surveys, repeated over time, such as the UK Countryside Survey. Species richness at any one location is a function of the habitat type, the management that habitat has received over time, the available species pool and the climatic and other constraints governing species type and abundance there, including drivers such as N deposition, sulphur deposition and ozone. Typical species richness values for a range of UK habitats are shown in Table 8 below. Note this shows average species richness across the UK in 2007 based on Countryside Survey data (Carey et al. 2008), and incorporates the influences mentioned above. Therefore, since N deposition is known to have an adverse effect on plant species richness, areas with lower N deposition would be expected to have higher species richness and vice versa.

Table 8. Great Britain results for plant species indicators in the vegetation main plots in Countryside Survey 2007 (Carey et al. 2008).

Broad Habitat	*Average species richness*
Broadleaved and mixed Yew woodland	*20.9*
Improved grassland	*14.3*
Neutral grassland	*20.4*
Calcareous grassland	*43*
Acid grassland	*19.6*
Dwarf, Shrub, Heath	*15.9*
Fen, Marsh, Swamp	*21.9*
Bog	*17.2*
Streamsides	*17.2*
Hedgerows	*14*
Roadside verges	*17.5*

3.7.3.2 Impact pathway

Summary of approach

- Nitrogen affects plant species richness in a large number of UK habitats, including acid grassland, sand dune grassland, mixed grassland, heaths, bogs, deciduous woodland.
- Based on a previous study (Caporn et al. 2012) we derived dose-response relationships for nitrogen deposition on species richness for four of these habitats: heathland, acid grassland, sand dune grassland and bogs. Full details of the equations can be found in Appendix C.
- Spatially explicit calculations were made for individual grid cells at 5x5km resolution. For each of the four habitats, in each grid cell, in each year, expected species richness was calculated based on the N deposition for that cell.
- Percentage difference in species richness from the reference year for that scenario was then calculated, shown in Figure 6, Figure 7, Figure 8, Figure 9 for the final year of each scenario analysis.

Changes in plant species richness, by habitat

The maps of change in species richness (Figure 6, Figure 7, Figure 8, Figure 9) reflect the spatial pattern of change in N deposition, combined with the location and species richness of each habitat. The log curves for three of the four habitats mean that the same change in N deposition will have a greater impact on species richness in areas of low N deposition than in areas of high N deposition, where the most sensitive species have already been lost.

Heathland habitat is concentrated in Scotland and in upland England and Wales. In the historical scenario, there are declines in species richness in eastern Scotland and south west England matching the changes in N deposition. The greatest increases in species richness are to be found in southern England and some parts of north west England, Wales and the western half of Scotland. In the future scenario, there are smaller but consistent increases in species richness, with the greatest increases occurring in the Pennines and northern England.

Acid grassland habitat is concentrated in Scotland, north west England and Wales. In the historical scenario, there are declines in species richness in eastern Scotland and south west England matching the changes in N deposition. The greatest increases in species richness are to be found in some parts of north west England, Wales and the western half of Scotland. In the future scenario, there are smaller but consistent increases in species richness, with the greatest increases occurring in the Pennines and north west England.

Dune grassland occurs along the majority of Great Britain's coastline, with the largest areas on western coasts, and a few large dune sites in eastern Scotland, Northumberland, Norfolk and Kent. This distribution is used for reporting of critical load exceedance for this habitat, and is derived from CEH Landcover (LCM2007) using the supra-littoral habitat class, with a 2km coastal buffer and occurrence of *Ammophila arenaria* (Marram grass) as a filter to exclude the majority of non-coastal dune habitat. This method seriously under-estimates the area of dune habitat in the UK, resulting in a figure of 43,000 ha (Table 10) compared with the figure of 71,500 ha from the UK National Ecosystem Assessment (Jones et al. 2011). The actual area is therefore around 70 % greater. In the historical scenario, there are declines in species richness in eastern Scotland and south west England matching the changes in N deposition. The greatest increases in species richness are to be found on the southern English coast and in Norfolk. In the future scenario, there are smaller but consistent increases in species richness, with no strong regional pattern.

Bog habitat occurs mainly in the north and west of Scotland, and parts of upland England and Wales. In the historical scenario, there are small declines in species richness in eastern Scotland and northern England matching the changes in N deposition. The greatest increases in species richness are to be found in some parts of north west England, north Wales and western Scotland. In the future scenario, there are smaller but consistent increases in species richness, with the greatest increases occurring in north west England.

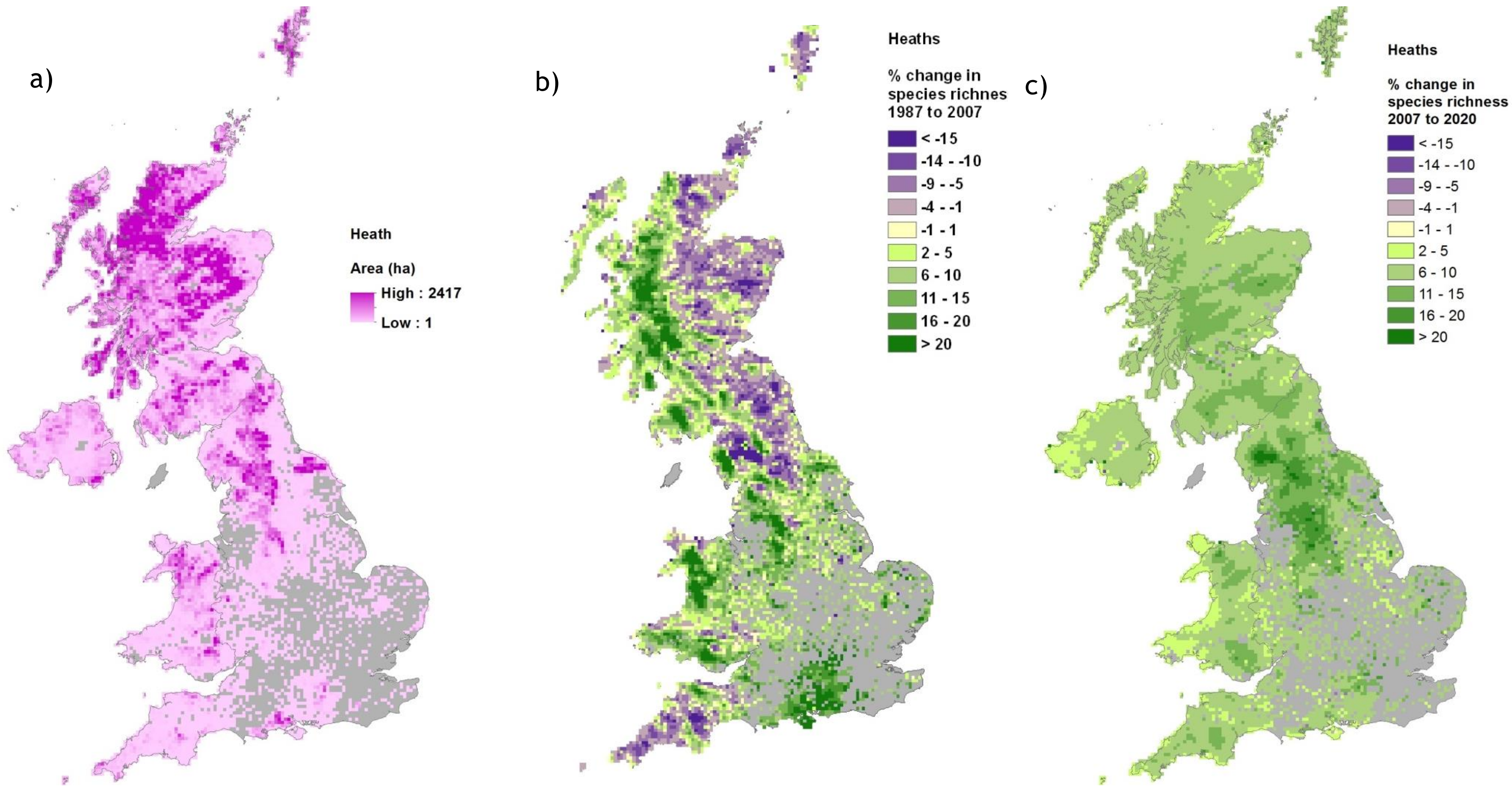


Figure 6. Heaths: Nitrogen impact on UK species richness showing a) habitat area (ha), spatial pattern of percentage species change due to N deposition in b) the historical emissions scenario and c) the future emissions scenario. Grey = habitat not present in that 5x5 km square. N.B. GB only in historical scenario.

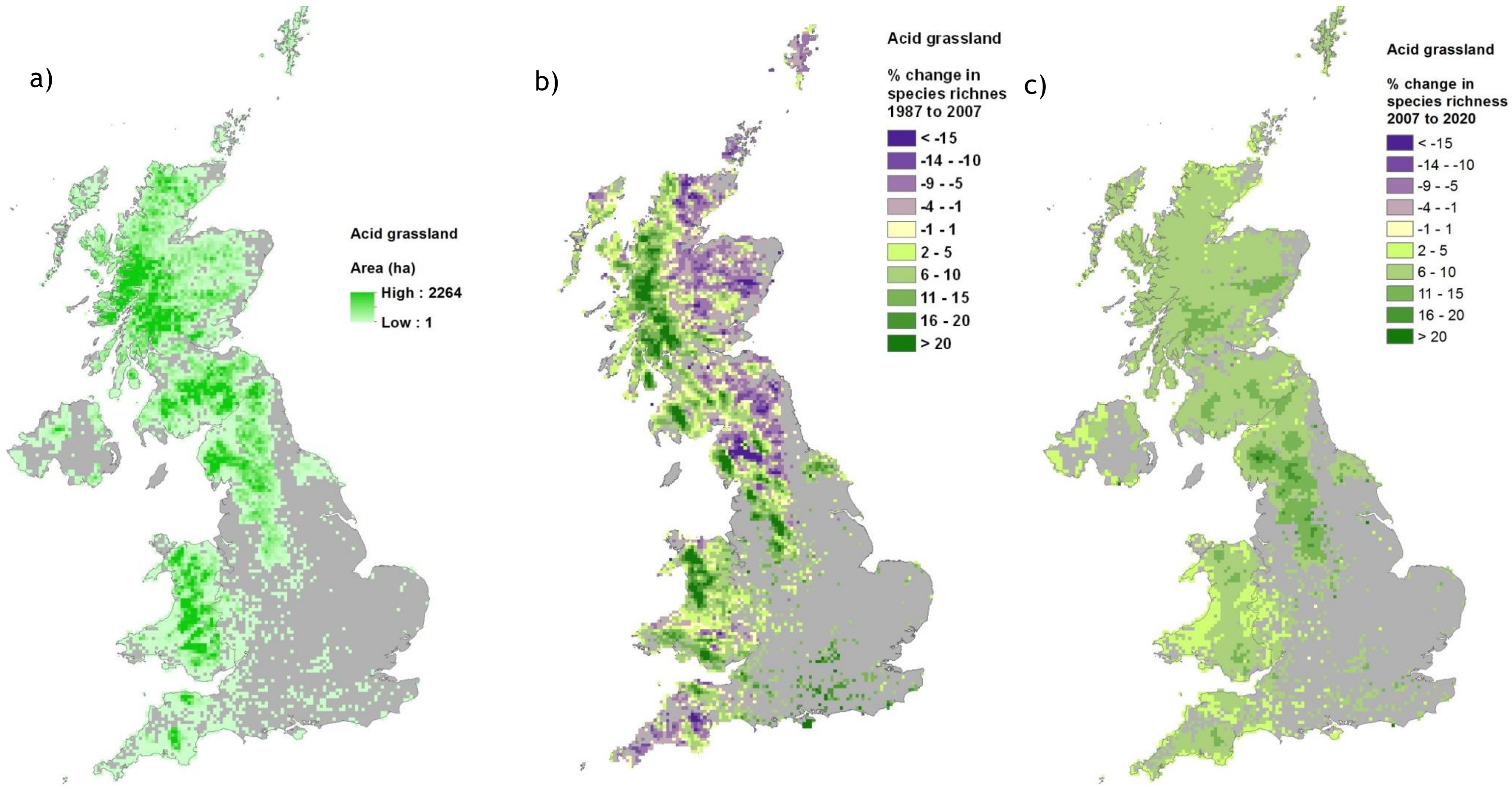


Figure 7. Acid grassland: Nitrogen impact on UK species richness showing a) habitat area (ha), spatial pattern of percentage species change due to N deposition in b) the historical emissions scenario and c) the future emissions scenario. Grey = habitat not present in that 5x5 km square. N.B. GB only in historical scenario.

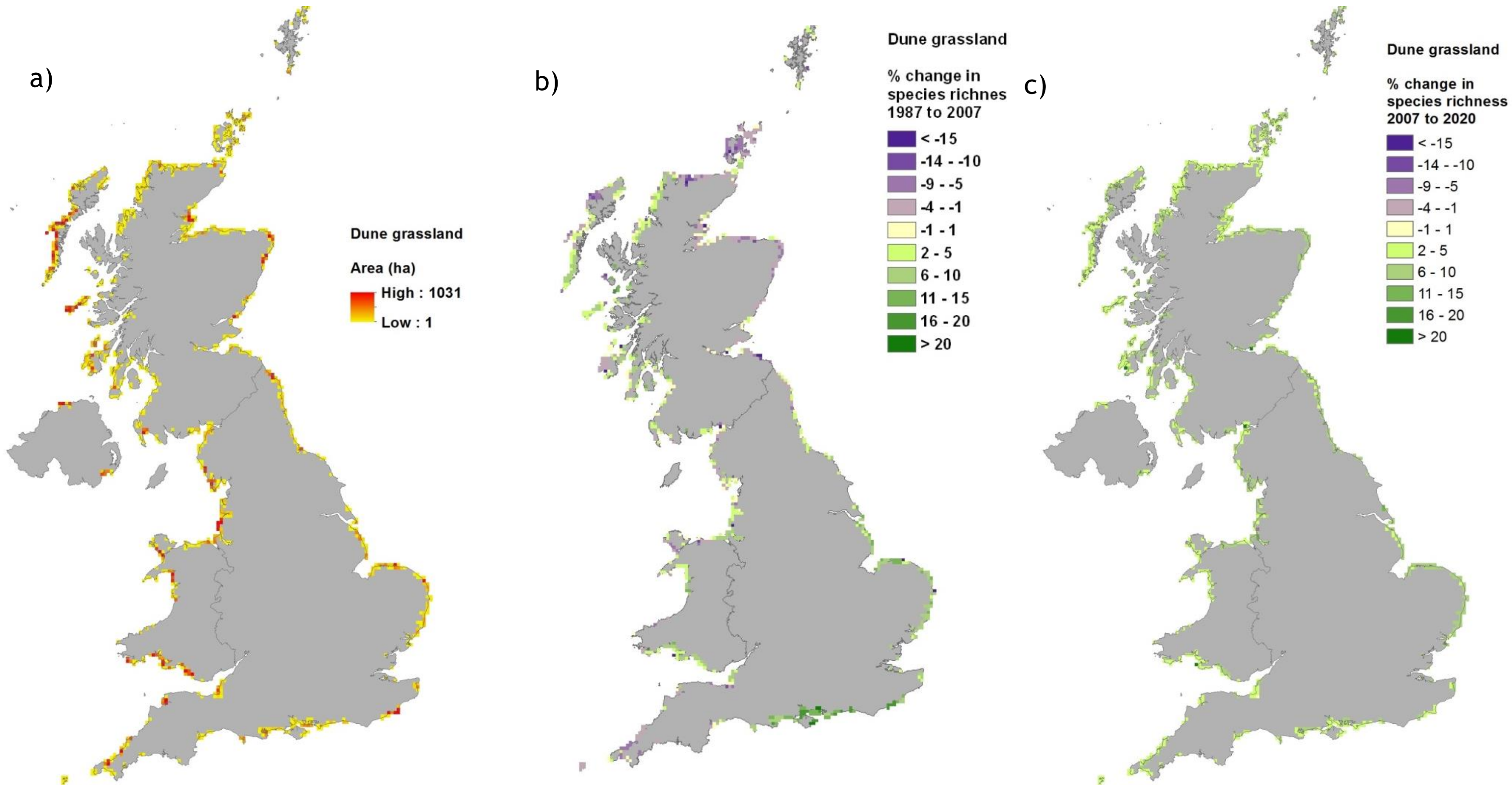


Figure 8. Dune grassland: Nitrogen impact on UK species richness showing a) habitat area (ha), spatial pattern of percentage species change due to N deposition in b) the historical emissions scenario and c) the future emissions scenario. Grey = habitat not present in that 5x5 km square. N.B. GB only in historical scenario.

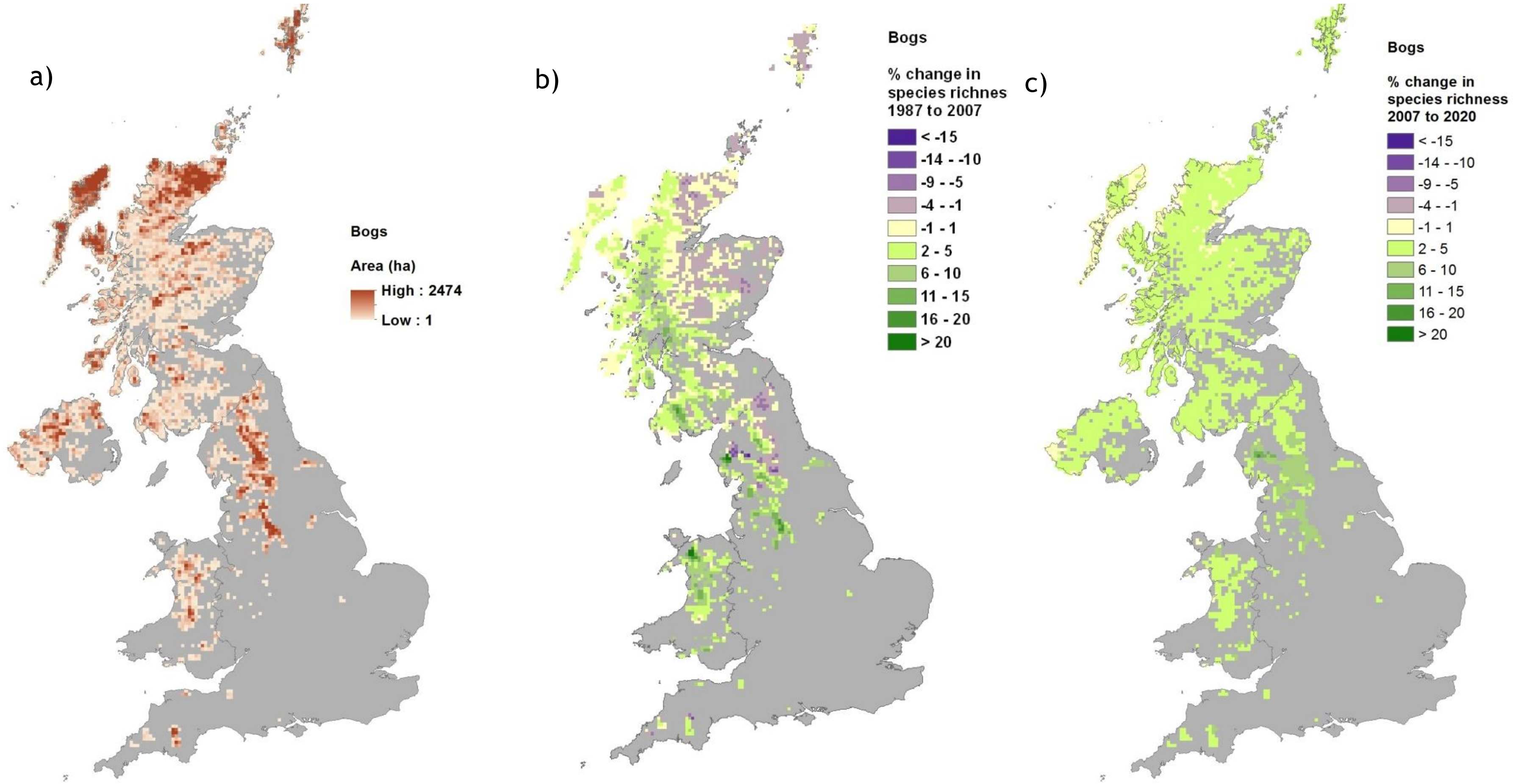


Figure 9. Bogs: Nitrogen impact on UK species richness showing a) habitat area (ha), spatial pattern of percentage species change due to N deposition in b) the historical emissions scenario and c) the future emissions scenario. Grey = habitat not present in that 5x5 km square. N.B. GB only in historical scenario.

3.7.4 *Selection of value transfer evidence*

Christie et al. (2010) and Christie and Rayment (2012) apply a choice experiment (CE) methodology to value changes in the level of provision of seven separate ecosystem service attributes. The attribute definitions and metrics for changes in their provision are:

- Wild food (% change in availability): non-rare food products such as berries and mushrooms that individuals might gather.
- Non-food products (% change in availability): natural products such as timber plants, fibre, cones, shells, stones that individuals might gather or photograph for ornamental, artistic or educational purposes.
- Climate regulation (change in '000 tonnes CO_2 sequestered per year): the role of habitats in storing CO_2 and helping to reduce impacts of climate change.
- Water regulation (change in '000 people at risk): management of habitats that influences likelihood of flooding events.
- Sense of place (% habitat achieving condition): the sights, sounds and smells found within a particular landscape, or linked to particular historical, cultural or personal events/activity.
- Charismatic species (status and number of species): threatened animal, amphibians, birds and butterflies species and populations that will be influenced by BAP implementation.
- Non-charismatic species (status and number of species): threatened trees, plants, insects and bug species and populations that will be influenced by BAP implementation.

The Christie et al. (2010) WTP study aimed to value spending on Biodiversity Action Plan (BAP) habitats, and was used as value transfer evidence for valuing nitrogen impacts on biodiversity (Jones et al. 2012; 2014), where impacts of nitrogen deposition on critical load exceedance were quantitatively scaled to values derived from the WTP study. In Christie et al. (2010), attribute levels were specified for nine regions of England, for England as a whole, Scotland, Wales, Northern Ireland, and the UK as a whole, for three BAP implementation scenarios: 'full implementation'; 'present BAP'; and 'no further BAP funding'. Full implementation represents enhanced levels of ecosystem service provision over the present BAP scenario. No further funding represents deteriorated levels of ecosystem service provision over the present BAP scenario. WTP values for the UK pooled model were used for value transfer.

Christie and Rayment (2012) document a separate study using a very similar Choice Experiment methodology, but applied to management of Sites of Special Scientific Interest (SSSI). In that study, focusing on the same ecosystem service attributes, we use the two ecosystem service attributes from Christie and Rayment (2012) which relate to species diversity, that for charismatic species and that for non-charismatic species. In this choice experiment, the funding scenarios used for these attributes were described as shown in Table 9, and specify a clearly quantified change in species richness.

Table 9. Ecosystem service attributes under the SSSI funding scenarios in the Christie and Rayment (2012) Choice Experiment.

Attribute	Increase SSSI funding	Maintain SSSI funding	Remove funding
Non-charismatic species	25% increase in the population or range of threatened species	No change in the population or range of threatened species	50% decline in the population or range of threatened species
Charismatic species	20% increase in the population or range of threatened species	No change in the population or range of threatened species	55% decline in the population or range of threatened species

We re-interpret these scenarios in order to conduct the value transfer analysis as follows. The 'Increase funding' scenario is analogous to a situation where species richness increases due to a decline in N deposition, with the Willingness To Pay (WTP) values associated with that scenario equating to a full 20% or 25% increase in species richness of charismatic, or non-charismatic species, respectively. The 'Maintain funding' scenario was defined by Christie and Rayment as the amount people are willing to pay to maintain current species richness, i.e. to avoid a decline in species richness that would be associated with removal of funding. We re-interpret this as analogous to a situation where species richness declines due to an increase in N deposition, and therefore as the amount respondents would be willing to pay to avoid a decline of 50% or 55% in species richness of non-charismatic, or charismatic species, respectively.

In Christie and Rayment (2012), WTP values were scaled according to an expert derived matrix. This allows separate attribution of ecosystem service value to individual habitats. They provide both values per hectare for each habitat, based on habitat area within SSSI sites in England and Wales, and aggregate values for England and Wales. In this study we used the values per hectare, in order to be able to scale up to the whole of the UK, using CEH Land cover data (LCM 2007) for habitat area. These values are shown in Table 10.

Table 10. Habitat area and WTP values (£ per hectare) for each of the habitats for which dose response functions were available from Christie and Rayment (2012). Area of habitat in the UK is calculated from CEH Landcover (LCM2007), see section 3.6.3.2.

			Non-charismatic species (£/ha)		Charismatic species (£/ha)	
Habitat	Area of habitat in SSSI (England & Wales) (ha)	Area of habitat in UK (ha)	Maintain Funding (species decline)	Increase Funding (species increase)	Maintain Funding (species decline)	Increase Funding (species increase)
Acid grassland	78,740	1,649,104	83.95	44.45	359.16	138.30
Heathland	280,192	2,117,466	112.17	46.40	604.80	181.98
Bogs	193,924	1,100,390	83.18	57.55	297.44	149.65
Sand dunes and shingle	11,876	42,983	66.52	58.10	307.34	195.35

3.7.5 Application of value transfer

For each grid cell in each year, the percentage change in species richness compared with the reference year was used to calculate the change in value due to changes in N deposition. The proportional change in species richness relative to percentage targets outlined in **Error! Reference source not found.** were scaled by the area of habitat in each grid cell to calculate the change in value. If species richness increased, the WTP for 'Increase funding' was used to calculate the benefit of gaining species, if species richness decreased, the WTP for 'Maintain funding' was used to calculate the cost of losing species. Thus, if species richness increased by 5 %, against the target of 25 % for non-charismatic species, this represents an increase in value of one fifth, i.e. 20 % of the WTP per hectare for that habitat. The total value was summed for all grid squares containing a habitat, and discounted in each year to calculate Net Present Value and Equivalent Annual Value.

3.7.6 Results, including 95% Confidence Intervals

Uncertainty analysis was only run for results from the future scenario, using value transfer for non-charismatic species. However, deterministic calculations are presented in Appendix D for both the future and the historical scenario using GB data for comparison. The variables in the models for Appreciation of biodiversity for which we assigned an uncertainty are listed below along with the assumptions made for the four habitats, for non-charismatic species (Table 11, with parameters summarised in Table 12). The Monte Carlo simulation was run with 500 000 iterations using latin hypercube sampling.

Table 11. Uncertainty parameters for Appreciation of biodiversity models

Variable	Assumptions and parameterisation
Spatially variable NHy deposition	We assumed that the uncertainty for each predicted value of N deposition was distributed log-normally with a standard deviation of 39.4% of the mean (this was derived from statistics reported in Table 4.2 of the RoTAP report on the accuracy dry NH_3 and wet NH_4^+ predictions and from model predictions of the proportions of dry NH_3 and wet NH_4^+that make deposited). We assumed a correlation of 0.99 between the values in 2007 and 2020.
Spatially variable NOx deposition	We assumed that the uncertainty for each predicted value of N deposition was distributed log-normally with a standard deviation of 26% of the mean (this was derived from statistics reported in Table 4.2 of the RoTAP report on the accuracy dry NO_2 and wet NO_3^- predictions and from model predictions of the proportions of dry NO_2 and wet NO_3^- that make deposited). We assumed a correlation of 0.99 between the values in 2007 and 2020.
Response function for calculating species richness (slope of $y = a.\ln x + b$ relationship for acid grassland, heaths and dune grassland, $y = ax + b$ for bogs)	*Acid grass* We assumed the uncertainty in the model parameters were distributed normally with means $a_m = -14$ and $b_m = 65.16$ and standard deviations a_s =2.72 and b_{cs} =7.93. These parameters have a strong negative correlation (-0.99) which must be accounted for. We did not allow species richness to fall below 5.5 (50% of the smallest observed value). *Bogs* We assumed the uncertainty in the model parameters were distributed normally with means $a_m = -0.29$ and $b_m = 27.66$ and standard deviations $a_s = 0.11$ and $b_{cs} = 1.92$. These parameters have a strong negative correlation (-0.94) which must be accounted for. We did not allow species richness to fall below 7.5 (50% of the smallest observed value). *Dunes* We assumed the uncertainty in the model parameters were distributed normally with means $a_m = -20.5$ and $b_m = 98.25$ and standard deviations a_s =6.15 and b_{cs} =15.06. These parameters have a strong negative

	correlation (-0.99) which must be accounted for. We did not allow species richness to fall below 12.5 (50% of the smallest observed value). *Heathlands* We assumed the uncertainty in the model parameters were distributed normally with means $a_m = -11.3$ and $b_m = 49.67$ and standard deviations a_s =2.27 and b_{cs} =6.56. These parameters have a strong negative correlation (-0.99) which must be accounted for. We did not allow species richness to fall below 3.5 (50% of the smallest observed value).
Percentage area of heathland in 5x5km square	Based on expert opinion we assumed that the uncertainty in the percentage of heathland across the UK was distributed with a triangular distribution with limits ±5% of the mean.
Maintain/Increase Funding	We estimated these variables based on the information in Christie et al. (2012). We assumed that both were distributed log-normally with standard deviation 65% of the mean. This uncertainty did not account for the uncertainties accumulated when aggregating from the value per hectare for each habitat as this information was not available to us.
Average change in NHy emissions	We assumed that the uncertainty in emissions was normally distributed with mean 9546 and standard deviation 974. This was based on estimated uncertainties in base year emissions given in Table 3-1 from Misra et al. (2012).
Average change in NOx emissions	We assumed that the uncertainty in emissions was normally distributed with mean 279521 and standard deviation 14261. This was based on estimated uncertainties in base year emissions given in Table 3-1 from Misra et al. (2012).

Table 12. Parameters for response functions for species richness and N deposition, by habitat.

	Means		Standard deviations		Correlations
	a_m	b_m	a_s	b_s	
Acid	-14.0	65.15	2.72	7.93	-0.99
Bogs	-0.29	27.66	0.11	1.92	-0.94
Dunes	-20.5	98.25	6.15	15.06	-0.99
Heathlands	-11.3	49.67	2.27	6.56	-0.99

3.7.6.1 Results for the future scenario.

Results of the uncertainty analysis are shown in Table 13 and Appendix D. For uncertainty analysis of nitrogen on appreciation of biodiversity, we present the mean from the deterministic calculations and the 95% Confidence Intervals from the uncertainty analysis.

In the future scenario, the benefit to appreciation of biodiversity as a result of declining N deposition, calculated for non-charismatic species (Table 13), was highest for heathland, with a mean EAV of £17.2m (£2.4m to £55.6m, 95% CI), followed by acid grasslands with an EAV of £12.3m (£1.8m to £39.8m, 95% CI). The combined benefit (EAV) for the four habitats was £32.7m (£36.4m to £298.0m, 95% CI). Deterministic results of the historical scenario are shown in Appendix C. Full results of the uncertainty analysis are presented in Appendix D. Figure 10 shows graphically the impact by habitat in each of the UK countries, which reflects the spatial pattern of occurrence of habitat within each country combined with the changes in N deposition within each. In England, Scotland and Northern Ireland, impacts on heathland provide the largest benefit, while in Wales impacts on acid grassland provide the greater benefit. This is largely a result of differences in the extent of these habitats in the four countries. Figure 11 shows the proportion of EAV that is due to changes in deposition of oxidised N and changes in deposition of reduced N. Only 10 – 15 % of the valued benefits to appreciation of biodiversity result from changes in deposition of reduced forms of N, the rest is due to reductions in oxidised N deposition.

Table 13. Net Present Value and Equivalent Annual Value of nitrogen impacts on 'appreciation of biodiversity' for non-charismatic species, by country and by habitat, Future scenario.
Habitats: acid grassland, heathland, dune grassland, bogs and total value. 95% CI presented for UK totals only, full details in Appendix D.

Net Present Value (2007 – 2020)	Acid grassland	Heathland	Dunes	Bogs	**Total 4 habitats**
England	£30,404,000	£41,806,000	£963,000	£12,764,000	**£85,937,000**
Wales	£19,434,000	£9,595,000	£268,000	£1,671,000	**£30,968,000**
Scotland	£75,301,000	£120,916,000	£1,095,000	£14,715,000	**£212,027,000**
Northern Ireland	£1,175,000	£4,371,000	£80,000	£2,093,000	**£7,719,000**
UK (95% CI)	**£126,314,000 (£18,900,000 to £411,100,000)**	**£176,688,000 (£27,700,000 to £577,000,000)**	**£2,406,000 (£140,000 to £8,500,000)**	**£31,244,000 (£2,900,000 to £109,900,000)**	**£336,652,000 (£143,700,000 to £3586,100,000)**

Equivalent Annual Value	Acid grassland	Heathland	Dunes	Bogs	**Total 4 habitats**
England	£2,951,000	£4,058,000	£93,000	£1,239,000	**£8,341,000**
Wales	£1,886,000	£931,000	£26,000	£162,000	**£3,006,000**
Scotland	£7,309,000	£11,736,000	£106,000	£1,428,000	**£20,580,000**
Northern Ireland	£114,000	£424,000	£8,000	£203,000	**£749,000**
UK (95% CI)	**£12,260,000 (£1,800,000 to £39,900,000)**	**£17,150,000 (£2,700,000 to £56,000,000)**	**£234,000 (£10,000 to £820,000)**	**£3,033,000 (£300,000 to £10,700,000)**	**£32,676,000 (£4,400,000 to £109,700,000)**

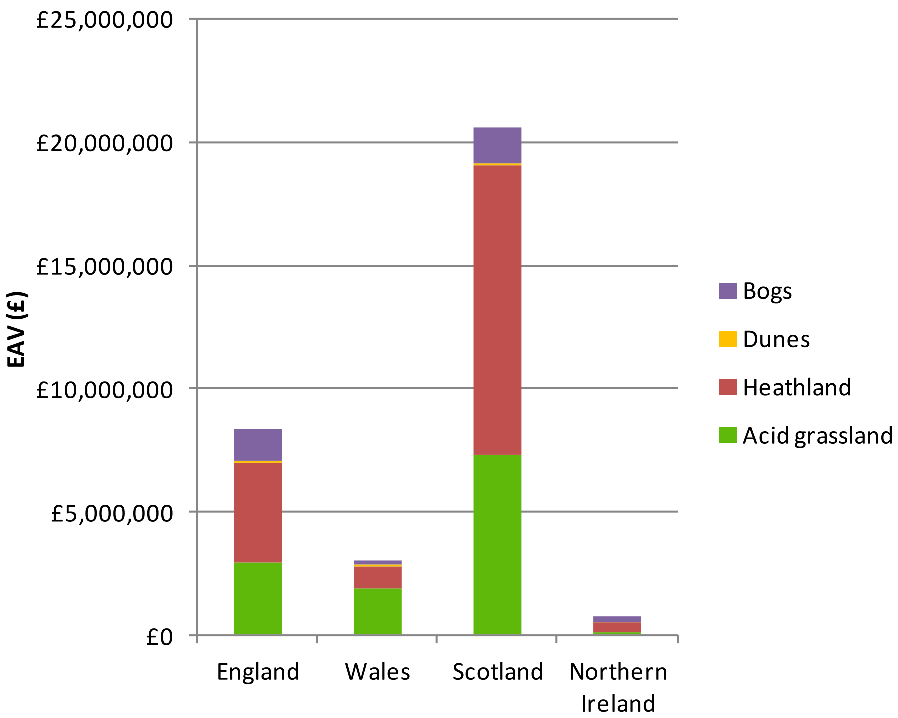


Figure 10. Equivalent Annual Value for non-charismatic species, Future scenario, graphed by habitat and by country.

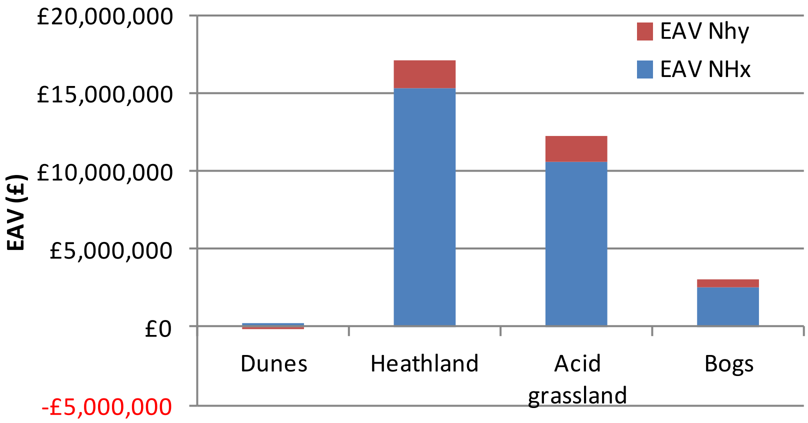


Figure 11. Equivalent Annual Value for reduced N (NH_y) and oxidised N (NO_x) for non-charismatic species, Future scenario, by habitat.

3.7.7 Damage costs for nitrogen dioxide and ammonia impacts on 'appreciation of biodiversity'

Damage costs per tonne decline in nitrogen oxides emitted, expressed as nitrogen dioxide, and per tonne decline in ammonia emitted are shown for impacts on the ecosystem service 'appreciation of biodiversity' in Table 14. Full results of the damage costs for each habitat, including uncertainty analysis are shown in Appendix D. The damage costs for ammonia are a factor of four greater than for nitrogen dioxide.

Table 14. Damage costs by habitat for impacts on 'appreciation of biodiversity'. £ per tonne decline in pollutant emitted (95% CI).
Positive values represent a net benefit i.e. increasing species richness as a result of falling N deposition. Negative value for NH_3 for dunes (in red) reflects a net cost, i.e. increased damage to dune species richness from localised increases in NH_3 deposition in this scenario which outweigh decreases in NH3 deposition to dunes elsewhere. This greater spatial heterogeneity is one outcome of applying the more realistic spatial calculation of impact.

Habitat	NO_2 (£/ton)	NH_3 (£/ton)
Acid grassland	£55	£195
Heath	£38	£175
Dunes	£0.9	-£0.5
Bogs	£9	£45
Total 4 habitats (95% CI)	**£103 (£33 to £237)**	**£414 (£139 to £1022)**

3.7.8 Discussion of results

3.7.8.1 Comparison of values with previous reports.

The total EAV for N impacts on the service 'appreciation of biodiversity' in the UK is £32.7 million in this study compared with £64.8 million in the future scenario from report NE0117. The damage costs calculated from these figures will therefore also differ. This is due to a number of reasons, outlined below:

-Different habitats combine to make up the total. Report NE0117 included response functions for two habitats not covered in this study: calcareous grassland which had a very high WTP associated with it, and woodland. Using the revised methodology which links WTP to changes in species richness, response functions were not available for these habitats. An additional habitat, dune grassland, was incorporated in the new methodology but the low WTP for this habitat, combined with its low area in the UK, added little to the total EAV. Omitting calcareous grassland and woodland from the NE0117 study would have reduced the EAV by 62%.

-Different methodologies for linking habitat/species damage to valuation, and different value transfer studies (Christie et al. 2011; 2012). The method in report NE0117 used critical load exceedance as a proxy for habitat damage, aligned to a choice experiment where populations or range of non-charismatic species either increased or decreased according to levels of funding for site management (Christie et al. 2011). In report NE0117, the decision was made to bound these changes between levels of zero or 100% critical load exceedance that might occur for each habitat under different levels of average UK N deposition. The approach in this report uses a different valuation study (Christie et al. 2012) where the choice experiment was defined more clearly in terms of percentage increase or decrease in populations or range of non-charismatic species according to levels of funding for site management. This provided direct linkage to response functions for changes in species richness due to N deposition, allowing a clearer impact pathway and a more transparent methodology.

-Spatially explicit N deposition and habitat data vs UK average N deposition. Report NE0117 used a simple average UK N deposition to calculate impact across the UK. This report uses spatial data at 5 x 5 km resolution which serves two purposes – it uses the N deposition where the habitats are located and the impact is calculated based on the quantity of habitat at each location. Sensitivity analysis of the methodology in this report evaluated the choice of N deposition data, by using the average N deposition across all locations where each habitat occurs rather than the UK average N deposition.

This resulted in a decrease in values for dunes of 20 %, no change for heathland, a 5 % increase for heathland and an 8 % decrease for bogs. Making the calculations spatially explicit by using N deposition and habitat quantity in each grid square led to larger changes: calculated values for dunes were 23 % lower than the estimate using UK average N deposition, values for heathlands were 14 % greater, values for acid grassland were 27 % greater, and values for bogs were 5 % lower.
-The final reasons for differences in the two reports are due to differences in the scenarios used. The different length of scenario period (2005 to 2020 in NE0117, and 2007 to 2020 in this report) caused differences due to the discounting of future benefits. However, greater differences are due to different input data for N emissions and deposition. Their respective baseline years differ (both based on CBED deposition). The two reports also use FRAME deposition data for 2020 which are based on different emission projections. FRAME modelling used in report NE0117 used UEP33 emission projections, while the FRAME modelling used in this report incorporated the more up to date UEP43 emission projections for NOx and changes in agricultural emissions of ammonia from Defra draft report AC0109. The latter study shows a slightly smaller net change in NHy deposition, average change of 11 % from 2007, compared with the UEP33 projections which show a 14 % decline in NHy deposition from 2005. More importantly, the average figure hides spatial variation across the UK, with some grid squares showing increases rather than decreases in NHy deposition, particularly in dune grassland. The effect of differences in the input N data in the different scenarios cannot easily be compared, given the other changes above, but are likely to have a much greater effect on the damage costs for ammonia than for nitrogen dioxide. This is because in the UEP33 scenario, ammonia emissions decline by 14 % over the scenario period, while in the AC0109 report NH3 emissions only decline by 6 %.

3.7.8.2 Damage costs.

The damage costs presented here for nitrogen dioxide can be widely used in policy appraisal, since they reflect the result of large declines in emission and in deposition of oxidised N in the scenario evaluated, and the resulting impact on this ecosystem service. However, the damage costs for ammonia are only considered meaningful in the context of small declines in ammonia emissions due to the context of the scenario evaluated (a 6% decline) and do not adequately quantify the potential benefits which could be achieved by larger-scale reductions in emissions of ammonia. This is because the relationship between emissions and deposition of reduced forms of N is non-linear and has a strong spatial context. Under the UEP43 scenario, changes in deposition of reduced N are small, with deposition increasing in some areas and decreasing in others, with these values often cancelling each other out when calculating the total EAV and therefore the damage cost at the UK scale. It is suggested that the ammonia damage costs can be used for policy appraisal for declines in ammonia emission of up to 10%. The methodology for calculating N impact on Appreciation of Biodiversity makes no distinction between effects of increasing or declining N emissions. Therefore the damage costs can be applied for increases or decreases in emissions. Calculations of impacts on carbon sequestration and timber production in the previous methodology (Jones et al. 2012) apply a dose-response relationship calculated specifically for declines in N deposition, and the resulting damage costs for those services can only be applied for declines in N deposition.

Obtaining improved damage cost figures for larger scale changes in ammonia
Reduced N now makes up the bulk of total N deposition, comprising roughly 68 % of the N deposition in 2007, and this proportion is projected to increase. Moreover, ammonia emissions are actually projected to increase slightly beyond 2020 (Defra report AC0109). In order to obtain meaningful damage costs for ammonia, to show the potential benefit of reducing ammonia emissions, it is therefore suggested to create a hypothetical scenario in which ammonia emissions decrease (or alternatively increase) by a substantial amount, in the order of ± 50%. The full impact pathway can then be re-evaluated, running dispersion/deposition models such as FRAME to estimate deposition spatially, and calculating the resulting impact on a range of ecosystem services, together with uncertainty analysis to show the 95% confidence intervals around the assessment of values.

3.7.8.3 Knowledge gap for charismatic species.

Willingness To Pay values for charismatic species are roughly a factor of 5 greater than for non-charismatic species. While the majority of species known to be affected by N so far fall within the non-charismatic group, there is emerging evidence of impacts on species that fall within the charismatic group such as butterflies (WallisDeVries and Van Swaay, 2006) and birds (via impacts on prey items, Nijssen et al. 2001). It could also be argued that some species of plants such as orchids, while technically falling within the non-charismatic group as defined by Christie and Rayment (2012) are likely to be seen as charismatic by many members of the public and would attract a higher WTP value. At present, it is not possible to model impacts on charismatic species within this valuation approach, due to a lack of dose response functions for charismatic species. This remains an important evidence gap that requires further research.

3.7.9 Key assumptions and caveats

- The dose response relationships assume N deposition is the only control on species richness. i.e. they don't include climatic influences, or account for variation in species richness around the UK. The latter will be possible in future once spatially explicit modelled species richness data are available. This is a planned focus for an ongoing NERC BESS project.
- As in the Jones et al. (2012) study, there remain strong assumptions linking the WTP values from Christie and Rayment (2012) to changes in biodiversity. The method developed here makes that link more explicit by matching changes in species richness due to N to changes in species populations valued in the Choice Experiment. Since respondents to the Choice Experiment were asked to value changes in species populations, the study was deemed appropriate for the purposes of value transfer using this link. However, until a specific WTP study is designed to value impacts of nitrogen deposition, there are no other studies which provide a better source of valuation information.
- We show results for non-charismatic species and estimate likely values for charismatic species but using the dose response functions for non-charismatic species. By far the greatest evidence is for impacts on plants which, even for orchids and similar species of high public interest, fall into the 'non-charismatic' category as defined by Christie and Rayment (2012). However, there is some evidence for N impacts on charismatic species such as red-shrike and butterflies, showing that N can impact animals and birds at higher trophic levels. Therefore we recommend that further work is required to develop dose response functions for charismatic species.
- We note that the Choice Experiment valued declines in populations of threatened species within SSSIs, whereas we make the link to actual loss of species from the landscape. Generally, but not always, threatened species are those with poor competitive ability and as such are likely to be particularly sensitive to the eutrophication effects of N deposition. Furthermore, declines in species populations are likely to lead to increased risk of local extinction in the future, even if species are not lost from the landscape at present. In other words, the dose response relationships set a harsher condition on evaluating species change, requiring actual

loss of species, and could be said to be a cautious interpretation of outcomes from the Choice Experiment.

- Lastly, we make the assumption that changes in N deposition will result in immediate changes in species richness. We know that with increases in N deposition there are lagged responses of plant species abundance, of 1-3 years for sensitive lower plants, and typically 5+ years for higher plants. With recovery from declining N deposition, the lag times of response are even longer for higher plants due to the ongoing nutrient contribution by accumulated soil N stocks even once N deposition declines below the critical load for a habitat. Such effects can persist for many decades, and there may never be full recovery to previous levels of species richness, even with restoration measures.

- A brief exploration of the impact of lags on the valuation for dune grassland in Great Britain only shows that introducing a 5-year lag time in response of species richness reduced the benefit in terms of non-charismatic species in dune grassland by a factor of one third from £110,000 (EAV) to £68,000 (EAV) in the historical scenario, and by a factor of two from £226,000 (EAV) to £98,000 (EAV) in the future scenario. The impact on the future scenario is greater due to the shorter duration of the scenario.

3.7.10 Recommendations for further work

- Develop dose response functions for charismatic species and apply them within this valuation framework.

- Develop dose response functions for non-charismatic species in other habitats where there is evidence for N deposition impacts on species richness, such as broad-leaved woodland and mixed (neutral) grasslands.

- Refine the existing dose response relationships for non-charismatic species, to include apportioning the possible co-correlated influence of climate and other pollutants on plant species change.

- Conducting ammonia specific emission scenarios, where ammonia emissions change by up to 50% to evaluate the impact of large-scale changes in ammonia. Damage costs presented here are only recommended for use with changes in ammonia of up to 10.

- Conduct specific valuation studies for assessing air pollution impacts on biodiversity.

4 WP3. Horizon scanning

4.1 Identifying gaps in knowledge and timescales to economic valuation

This section provides recommendations as to research, data collation exercises or meta-analysis studies which need to be carried out to address the key gaps in the methodology identified in work package 1. Some of this information draws on group discussions in the workshop held as part of work Package 1, but also draws on the expertise of project partners and their colleagues in ongoing projects.

There is some overlap with this section and the criteria developed in work package 1 in order to prioritise which services to take forward to detailed spatial valuation within this study (work package 2). We do not repeat that exercise, but summarise here the main knowledge gaps in Table 15. This table also includes ongoing or upcoming projects which might contribute to further development of ecosystem service valuation, and an estimate of the amount of time required to address each of the knowledge gaps. Further detail is provided for those services we believe could be taken through to economic valuation in section 4.2.

We would also like to point out that in Table 15 we separate out effects of nitrogen and sulphur. However, for many ecosystem services some of their impacts are intrinsically linked, particularly with respect to acidification of soils and freshwaters, and it is difficult to separate out effects in this type of analysis. Relationships are not always linear and sometimes complex models are required to estimate the nature and direction of change for a service over a specified timescale.

Table 15. Summary of knowledge gaps for science or valuation for quantifying impacts of air pollution on each ecosystem service, and identification of projects or studies which might help fill those gaps.
Note: Nitrogen and Sulphur effects both contribute to acidity effects – for clarity of presentation, acidity effects are presented here only under 'sulphur' to avoid repetition. [1]***Service*** *also includes potential scale of impact of atmospheric inputs on that service, provided for guidance only and judged using expert knowledge;*
[2]***New/existing funded studies*** *covers those that will deliver new information in the next two years;*
[3]***Timescale to completion*** *includes steps needed with further investment.*

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
Provisioning Services				
Crop Production				
Nitrogen (small impact)	(1) None for most crops (as dose response functions for N & yield are available for fertilizer applications) (2) locations for biomass crops (new crops)	(1) None for most crops (market prices of crops and N fertiliser are available) (2)Location of yield of biofuel crops more difficult to map	(1,2) None identified.	(1) 6 – 12 months (data collation and analysis required) (2) 12 -24 months (data collation and analysis required)
Sulphur (small-medium impact)	(1) None for most crops (as dose response functions for S & yield are available for fertilizer applications) Notes – (i)farmers are now applying S due to reduced atmospheric inputs and S deposition had some fungicidal effect – these costs could be valued; (ii) published data from field release SO_2 exposure of barley is available	(1) None (market prices of crops and S fertiliser should be available)	(1) None identified.	(1) 6 – 12 months (data collation and analysis required)

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
	from 1980s, but only at v. High concentrations			
Ozone (medium impact)	(1) Flux models available for wheat, oilseed rape, tomato and potato. New experiments needed for other crops (AOT40 could be used, as in Mills et al., 2011 UK study, but that study showed different patterns for AOT40 relative to flux) (2) Impacts of reduced yield on farmer decision making (discussed in study conducted for France, Humblot et al., 2012)	(1) None (market prices of crops are available) Maps and data for UK tomato production needed	(1) None identified.	(1) <6 months for oilseed rape and potato (all data available) > 2 years for others (new field/solardome experiments needed) (2) 12 -24 months
Livestock Production (& Shellfish)				
Nitrogen (small impact)	(1) None for dose response function, as this is available for N and yield in improved pastures or silage crop used for beef/dairy (2) Need to approximate complex animal production systems (3) Impacts on shellfish production (water quality class information on growth is available)	(1,2) None (market prices of beef, dairy, concentrates and N fertiliser are available) (3) None – market prices are available for shellfish	(1,2,3) None identified.	(1,2) 6 – 12 months (data collation and analysis required) (3) 12 -24 months (possibly longer, data collation and analysis required)
Sulphur (small impact)	(1) None for dose response function, as this is available for S and yield in improved pastures or silage crop used for beef/dairy (2) Need to approximate complex animal production systems	None (market prices of beef, dairy, concentrates and S fertiliser are available)	(1,2) None identified.	6 – 12 months (data collation and analysis required)
Ozone (small - medium impact)	(1) Dose response function for ozone and yield in improved pastures or silage crop used for beef/dairy (2) Dose response for high input pasture (3) Need to approximate complex animal production systems	None (market prices of beef, dairy, concentrates and N fertiliser are available)	(1) PhD at CEH Bangor on ozone effects on pasture (student in year 2) (2,3) None identified	(1,2) 6 – 12 months (Dose-response function available in autumn for intensively managed and grazed pasture) (3) < 6 months for beef/dairy (using unimproved pasture functions derived in recent ozone umbrella contract)
Timber Production				
Nitrogen	(1) How to incorporate scenarios	(1,2) None (forestry financial models are	(1) Potential for use of 4 x N treatment of	(1) 6 -12 months

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
(medium impact)	of changes in N into forest growth models; (Note: Locations of trees in UK and tree timber stocks are known) (2) Analysis of UK monitoring data for forest	available, or timber values can be approximated) Need to take into account valuation based on value of timber, pulp and biomass for burning. *Note: demand may change in future scenario due to reduced paper usage and increased biomass demand*	silver birch in solardomes and Edinburgh University PhD study on N and sitka spruce; *Note: both need extrapolation to mature trees as described for ozone* (2) EU ECLAIRE project - empirical analysis of European ICP Forests monitoring data being conducted	(data collation and analysis required) (2) 12- 24 months if including UK data which will need collating and analysing
Sulphur (none to very small Impact for S, impact of acidification)	(1) Dose response functions for S and tree growth taking into account fertilizer and acidification effects, for UK species (2) How to incorporate scenarios of changes in S into forest growth models	(1,2) None (forestry financial models are available, OR timber values can be approximated)	(1) Some new evidence relating S deposition to tree ring growth	(1,2) 6 -12 months (data collation and analysis required)
Ozone (medium impact)	(1) How to incorporate scenarios of changes in ozone into forest growth models	(1) None (forestry financial models are available, OR timber values can be approximated)	(1) ICP Vegetation/EU ECLAIRE study on modelling this for Europe EU ECLAIRE O3 and N experiment for silver birch (7 x O3, 4 x N interactions)	(1) Methods will be finalised in ca. 1 month, Progress for UK could be made in < 6 months using existing response function; silver birch functions available by end of year
Water supply				
Nitrogen (small impact)	(1) Dose responses for changes in tree growth with N and corresponding change in water use, and therefore runoff and recharge to groundwater (i.e. effective rainfall)	(1) Value of water as a commodity (may be available already from water companies; some analysis by NEA)	(1) None identified	(1) 12 -24 months (data collation and new modelling required)
Sulphur (small impact)	(1) Dose responses for changes in tree growth with S and corresponding change in water use, and therefore runoff and recharge to groundwater (i.e. effective rainfall)	(1) Value of water as a commodity (may be available already from water companies some analysis by NEA)	(1) None identified	(1) 12 -24 months (data collation and new modelling required)
Ozone (untested, probably small)	(1) Dose responses for net changes in tree growth, stomatal control and therefore water use with ozone, and therefore runoff and recharge to groundwater (i.e. effective rainfall)	(1) Value of water as a commodity (may be available already from water companies)	(1) EU ECLAIRE project experiments with O3 and silver birch	(1) Needs hydrological modelling - progress could be made in 12 - 24 months, could also infer from other drivers of change in tree growth

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
Regulating Services				
Water regulation (river flooding)				
Nitrogen (small impact)	(1) Dose responses for changes in tree growth with N and corresponding change in water use, and therefore runoff and recharge to groundwater (i.e. effective rainfall) (2) Some information available on N effects on sphagnum in blanket bogs causing increased overland flow	(1) Value of avoided flooding. Needs to be calculated spatially, and against current flood risk at each location, therefore may involve substantial work.	(1,2) None identified	(1) 12 -24 months (data collation and new modelling required) (2) >2 years. Dose response functions not available, more data needed.
Sulphur (small impact)	(1) Dose responses for changes in tree growth with S and corresponding change in water use, and therefore runoff and recharge to groundwater (i.e. effective rainfall) (2) Some information available on S effects on sphagnum in blanket bogs causing increased overland flow	(1) Value of avoided flooding. Needs to be calculated spatially, and against current flood risk at each location.	(1,2) None identified	(1) 12 -24 months (data collation and new modelling required) (2) >2 years. Dose response functions not available, more data needed.
Ozone (untested, probably small - medium impact)	(1) Dose responses for net changes in tree growth, stomatal control and therefore water use with ozone, and therefore runoff and recharge to groundwater (i.e. effective rainfall)	(1) Value of avoided flooding. Needs to be calculated spatially, and against current flood risk at each location.	(1) EU ECLAIRE project experiments with O3 and silver birch (flux-based), dose-response for other species (new data analysis needed to get to flux-based)	(1) 12 -24 months (data collation and new modelling required)
Carbon sequestration				
Nitrogen (medium - large impact)	(1) All habitats Primarily impacts on long-term soil C changes (2) Woodlands:	None (carbon can be valued)	(1) All habitats: (1.1) NERC UK Soil Observatory project is conducting analysis of spatial and temporal patterns in the Countryside Survey topsoil C data. Should reveal if there is a N and / or acidity (N+S) signal for any habitat over last 25 years (1.2) Wales Glastir Monitoring and Evaluation Project analysis of CS soils for change in C in topsoil	(1.1) 6 – 12 months (1.2) 4 years (available at end of current project) (2) Woodlands, 12 -24 months

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
	Data is available but needs sourcing on which species grown where in UK (e.g.forest inventories and CS data). (3) Heathlands: -Dose response functions linking N and long-term C allocation into soils (4) Grasslands: Dose response function for grassland productivity and N for improved and semi-natural grasslands (may be available for improved grasslands from other European countries) (5) Peatlands: Dose response functions linking N and rates of peat formation (available evidence suggests non-linear response with initial (small) C gain followed by (potentially large) C loss if N triggers loss of peat-forming species		(2) EU ECLAIRE project - empirical analysis of ICP Forests data to derive functions (3) None identified (4) None identified (5) Peatlands: (5.1) Analysis of data from Whim experiment to derive thresholds for species change in EU ECLAIRE (5.2) Analysis of recent peat C accumulation rates vs N deposition and vegetation type based on survey and stratigraphic analysis of short peat cores over an N deposition gradient (5.3) NERC macronutrients: impacts of land-use change and climate interventions	(data collation and new modelling required) (3) Heathlands, 12 -24 months (more measurements needed) (4) Grasslands,6 – 24 months (data collation and analysis needed, including further analysis of Defra TU umbrella data from Wardlow) (5) Peatlands, (5.1) 12 -24 months (data collation and new modelling required) (5.2) 12 -24 months (data collation and new modelling required) (5.3) 3- 4 years
Sulphur (sulphur probable no impact, acidity small-medium impact)	(1) Woodlands (linking with acidity effects): (1.1) Dose response functions linking S and tree growth, including incorporation in tree growth models. (1.3) Dose response function for S and long-term C allocation into soils (note functions for acidity are available) (2) Heathlands (linking with acidity effects): (2.1)Dose response functions linking S and shrub growth	None (carbon can be valued)	(1) Woodlands: None identified (2,3,4) Peatlands, heathlands and grasslands: Whim bog (EU ECLAIRE funded), other data sources include CEH 'EHFI'	(1) woodlands, 12 -24 months for analysis of above and below-ground C accumulation rates based on tree ring analysis over time and across S (and N) deposition gradients (2) 12 -24 months for analysis of litter and soil C stocks across S and N deposition gradients, possibly using 14C to infer accumulation rates

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
	(2.2) Dose response function for S and long-term C allocation into soils (3) Grasslands: Dose response function for grassland productivity and S for improved and semi-natural grasslands (may be available for improved grasslands) (4) Peatlands: Empirical relationship between S and N dose, acidity and decomposition rates		experiments, TU experiments) (4)Peatlands: Results of a new study of S and N deposition effects reducing availability of labile C available shortly	(2,3,4) Peatlands, heathlands and grasslands > 2 years for analysis of NPP/biomass measurements across S and N deposition gradients, and within experimental acidity and N manipulation experiments (4) 12 -24 months for ongoing modelling and analysis to be completed, with usable outputs
Ozone (probably medium impact)	(1) Woodlands: -How to incorporate scenarios of changes in ozone into forest growth models -Dose response function for ozone and long-term C allocation into forest soils (2) Heathlands: - Dose response functions linking ozone and shrub growth -Dose response function for ozone and long-term C allocation into soils (3) Grasslands: -Dose response function for grassland productivity and ozone for improved grasslands.	None (carbon can be valued)	(1) ICP Vegetation/EU ECLAIRE study on modelling impacts on living tree biomass for Europe (excludes soil C sequestration) EU ECLAIRE O3 and N experiment for silver birch (2) None identified (3) PhD at CEH Bangor on ozone effects on pasture (student in year 2)	(1) Woodlands 6 – 12 months (Methods available in ca. 1 month, Progress for UK could be made in < 6 months using existing response functions but would be worth waiting for silver birch functions available in late autumn; We would need more experiments to quantify effects on soil C (but can be inferred via models for other modifiers e.g. x% reduction in root growth is equivalent to y% reduction in soil C)) (2) Heathlands > 2 years (new experiments needed) (3) Grasslands 6 – 12 months (improved grassland productivity functions likely to be available by January) We would need more experiments to quantify effects on soil C or Defra-funded analysis of soils in PhD study (but can be inferred via models for other modifiers e.g. x% reduction in

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
				root growth is equivalent to y% reduction in soil C))
Methane Emissions				
Nitrogen (medium)	(1) Multiple dose response functions linking N and habitat change with impacts on methane emissions; soil NH_4 effects on methanogens	(1) None (can be converted to carbon equivalents, and valued)	(1) Whim bog ongoing experiment (EU ECLAIRE)	(1) 12 -24 months (new analysis needed)
Sulphur (small-medium impact *via* acidity)	(1) Current methane emissions for semi-natural habitats (could use IPCC tier 1 default flux reporting) (2) Dose-response relationships between SO4 loading and CH4 emission (suppression of methanogenesis by sulphate reducing bacteria)	(1,2) None (can be converted to carbon equivalents	(1,2) None identified	(1) < 6 months (data analysis required) (2) < 6 months (Existing dose-response relationship from work by Gauci et al. could be used. This could be augmented/ validated for UK ecosystems with new measurements e.g. of EHFI SO4 addition experiments (12 -24 months)
Ozone (generalisations currently difficult due to diversity of responses, possibly medium)	(1) Dose-response function for ozone and methane emissions drawing all published data together (2) Other response functions may be required	(1,2) None (can be converted to carbon equivalents	(1) New data analysis being conducted at CEH as part of ECLAIRE project; new data from York University available soon (2) O3 and Nr – Whim bog cores experiment in 2014	(1) 6 – 12 months (application of new and updated analysis) (2) 2- 3 years (new experimental data to be generated)
N_2O Emissions				
Nitrogen (medium- large)	(1) New soil emission factors have been developed. Otherwise methodology already developed	(1) None (can be converted to carbon equivalents, and valued)	(1) IPCC reporting project. Defra GHG platform possibility	(1) 6 – 12 months (application of new and updated analysis)
Ozone (small)	(1) To be derived from reductions in crop vitality and yield leading to added fertilizer applications	(1) None (can be converted to carbon equivalents, and valued)	(1) None identified	(1) 6 – 12 months - ideally linked with study on effects on crop production
Quality of water for drinking				
Nitrogen (small impact)	(1) Spatial modelling of N on nitrate concentrations in the uplands	(1) Value of on-going water treatment costs, separated for nitrates (commercial information that may not be easy to access)	(1) None identified	(1) 6 – 12 months (new data collation and analysis)
Sulphur (Medium via acidity effects)	(1) DOC: (1.1) Spatial and temporal modelling of S effects on DOC (1.2) Upscaling functions for DOC Concentrations	(1) Treatment costs for DOC, health costs associated with carcinogenic disinfection by-products generated during the treatment of high-DOC water Treatment costs for DOC	(1.1) Analysis and synthesis of existing monitoring, survey and experimental data (1.2) S & N modelling using MADOC and	(1) 6 – 12 months (new data collation and analysis)

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
	(2) Acidity: (2.1)Spatial modelling of S on acidity (2.2) Upscaling functions for acidity	(2) Treatment costs for acidity	N14C to predict DOC (and soil C). NERC Macronutrients and EU ECLAIRE (2) None identified	(2) 12 -24 months (new data collation and analysis)
Cultural Services				
Recreational fishing				
Nitrogen (medium impact)	(1)Dose response functions for N and fish, probably only wild-angling)	(1) Value transfer for value of wild angling (salmon, trout etc.)	(1) Data from Sweden and Norway could be used	(1) 6-12 months (collation and application of data and functions)
Sulphur (medium impact)	(1)Dose response functions for S and fish (via acidity/ANC concentrations), probably only wild-angling)	(1) Value transfer for value of wild angling (salmon, trout etc.)	(1) None identified	(1) 6-12 months (collation and application of data and functions)
Appreciation of biodiversity (aquatic)				
Nitrogen (small-medium)	(1) Re-analysis of total N impacts, separating into oxidised and reduced N (2)Dose response functions for N and aquatic biodiversity (fish, birdlife, invertebrates, plantlife/algae, visual amenity etc.)	(1,2) Value transfer for value of aquatic biodiversity (fish, birdlife, invertebrates, plantlife/algae, visual amenity etc.)	(1,2) UCL continuing analysis; Upland waters monitoring network	(1,2) 12 -24 months (new analysis and application required)
Sulphur (medium)	(1)Dose response functions for S and aquatic biodiversity (fish, birdlife, invertebrates, plantlife/algae, visual amenity etc.) (via acidity/ANC concentrations)	(1) Value transfer for value of aquatic biodiversity (fish, birdlife, invertebrates, plantlife/algae, visual amenity etc.)	(1) Fish recovery analysis at CEH and Marine Scotland	(1) 6 – 12 months (some existing data, new analysis and application required)
Appreciation of biodiversity (terrestrial)				
Nitrogen (large)	(1) Dose response functions still needed for N and plant species richness in other habitats (neutral grasslands, calcareous grasslands, woodland – the latter two may not be affected) (2)Dose response functions may be possible for some 'charismatic' species	(1,2) More value transfer studies on pollution and biodiversity - method for calculating costs of restoration	(1,2) JNCC sources (needs analysis) MultiMOVE modelling (MNC) *Note: Valuation methods are being considered by VNN and NERC BESS (not specific to pollutants)*	(1,2) 6 - 24 months (for more in depth analysis)
Sulphur (small)	(1) Dose response functions linking S and biodiversity change (some models available)	(1,2) More value transfer studies on pollution and biodiversity - method for calculating costs of restoration	(1,2) None identified	(1,2) 12 - 24 months (for more in depth analysis)

Service[1]	Knowledge gaps for science	Knowledge gaps for valuation	New/existing funded studies[2]	Time-scale to completion of valuation[3]
	(2) Indirect effects of S/acidity on biodiversity via changes in N demand/N limitation			
Ozone (medium)	(1) Further development of dose response functions linking ozone and changes in plant species richness *Note: some evidence of effects on pollinating insects, but dose-response functions not available yet*	(1) More value transfer studies on pollution and biodiversity	(1) York and Newcastle studies on effects of ozone on conservation value of a semi-natural grassland (Keenley) through positive and negative indicator species	(1) 6 – 12 months (new analysis of CS data needed)
Aesthetics				
Ozone (Small - medium)	(1) Quantification methods for effects on visual appearance of natural environment (via early autumn, less vibrant autumn colours, senesced plant canopy)	(1) Not currently available	(1) None identified	(1) 6 – 12 months to quantify potential effects BUT unknown timescale to valuation as value transfer studies not available

4.2 Impacts on Ecosystem Services that could be quantified within the next 12 months

Taking the information presented in Table 15, we provide here a summary of those ecosystem services that we believe we could conduct an economic valuation of effects for the historical and/or future scenarios within the next 12 months. We have included the steps required where appropriate, and have also noted whether data sets and methods are available or would need further development and/or collation.

4.2.1 Provisioning services - Crop production

4.2.1.1 Nitrogen (small impact), 6-12 months

For high N input crops such as wheat and potato, the impact is likely to be quite small relative to the amount of fertilizer applied whilst for those with lower N requirements (e.g. oilseed rape), the proportion of N input from the atmosphere could be as high as 25 – 50%. Economic effects could be quantified using:

- Spatially available crop yield data (2006 and 2008 available at 10 x 10 km grid scale)
- UK N deposition data (prepared under Defra project AQ0827 at 5 x 5 km scale for current and future scenarios
- Fertilizer response functions (to be derived from the literature, with the potential to model the contribution of atmospheric inputs at locations where the trials were conducted)
- Cost of fertilizer applications
- Monte Carlo analysis of uncertainty

4.2.1.2 Sulphur (small – medium impact), 6-12 months

Due to controls on S emissions, S fertilizer is now being used to compensate for a lack of atmospheric deposition of S. Thus, the impact of sulphur has changed over time. Historical analysis may show a negative effect due to toxicity of sulphur compounds inhibiting growth, while at current S deposition levels, lack of sufficient sulphur as a macronutrient is also inhibiting growth. Impacts of the historical reduction in S emissions can be determined from:

- Analysis of published data from SO_2 exposure experiments conducted in the 1970s and 1980s. However, it should be noted that these were conducted in the field as additions to the then deposition at sites where the experiments were conducted (Sutton Bonington, near Loughborough and Littlehampton, Surrey); current ambient SO_2 concentrations are lower than these.
- Analysis of published data on the fungicidal effects of SO2 and S on damaging crop fungal diseases
- Spatially available crop yield data (2006 and 2008 available at 10 x 10 km grid scale)
- Fertilizer response functions (to be derived from the literature, with potential atmospheric inputs at locations the trials were conducted included)
- Cost of fertilizer applications
- Monte Carlo analysis of uncertainty

4.2.1.3 Ozone (medium impact), < 6 months

For oilseed rape and potato, the same approach used in Defra project AQ0827 can be used to determine effects on economic yield, using:

- Spatially available crop yield data (2006 and 2008 available at 10 x 10 km grid scale)
- Available OSRM ozone flux data at 10 x 10 km scale for 2006, 2007, 2008 and 2020[5]
- Farm-gate crop value
- Monte Carlo analysis of uncertainty

A further development would be to estimate cost of added fertilizer to compensate for lost yield

4.2.2 Provisioning services – livestock production

4.2.2.1 Nitrogen and sulphur (small impact), 6-12 months

Could be analysed, taking into account N fertilizer savings and S fertilizer costs, using:

- Spatial data for productive pasture (to be collated); simplest approach is to assume same N and S requirement for all of UK – a more detailed spatial analysis would require consideration of soil type, pasture quality and nitrate sensitive areas.
- N and S fertilizer response functions
- UK S and N deposition maps (available)
- N and S fertilizer application rates and costs
- Model taking change in grass production through to livestock production (available for lambs from Defra project AQ0815, substantial work needed to determine for beef production)
- Monte Carlo analysis of uncertainty

4.2.2.2 Ozone (small - medium impact)-impacts on un-improved pasture systems, < 6 months

The methodology used in this study could be adapted for beef and dairy systems, using dose-response relationships derived for impacts of ozone on unimproved pasture. This would require input on the complex animal production systems in order to take through to valuation.

[5] Defra may wish to consider moving to the EMEP4UK model

It would be preferable however, to wait until dose response relationships are developed for impacts of ozone on improved pastures.

4.2.2.3 Ozone (small - medium impact)-impacts on improved pasture systems, 6-12 months

Using new dose-response function likely to be available by end of year for current grass-clover mixtures (6 ozone treatments, PhD study) used in high input productive grasslands:

24h mean ozone based study:

- Spatial data for improved pasture (to be collated)
- Spatial data for 24h mean ozone data available from Defra project AQ0815
- Response function for effects on biomass production to be determined as part of PhD, Defra investment in forage quality analysis would significantly improve usefulness for economic assessment
- Model taking change in grass production through to livestock production (available for lambs from Defra project AQ0815, substantial work needed to determine for beef production)
- Costs of added feed to compensate for reduced fodder quality and quality
- Monte Carlo analysis of uncertainty

Flux-based study:

As above, but new flux maps would need to be generated using the flux-model parameterisations to be derived in the PhD study

4.2.3 Provisioning services - Timber production

4.2.3.1 Nitrogen (medium effect) and sulphur (none to small), 6-12 months

Within the next year it will be possible to conduct a relatively simple analysis without use of forest growth models:

- Spatial data for timber production (to be collated)
- Derivation of N (available) and S response functions (to be revisited)
- UK S and N deposition maps (available)
- Valuation based on felling price for timber, pulp (for paper) and biomass for burning (methods to be developed)
- Monte Carlo analysis of uncertainty

4.2.3.2 Ozone (medium impact), 6-12 months

Two approaches are possible in the coming year:
(1) Using LRTAP Convention flux-effect models, we can analyse effects on broadleaved trees using:

- Spatial data for tree distribution and tree age (to be collated)
- Spatial data for beech flux for 2006, 2007, 2008 and 2020 available from Defra projects AQ0815 and AQ0816
- Response function for effects on whole tree biomass determined as part of EU ECLAIRE project together with tree growth model for extrapolation to mature trees
- Value of timber
- Monte Carlo analysis of uncertainty

(2) Using LRTAP Convention flux-effect models for needle- and broad-leaved trees, and new silver birch flux-effect relationship from EU ECLAIRE project, we can analyse effects using:

- Spatial data for tree distribution and tree age (to be collated)

- Spatial data for beech flux for 2006, 2007, 2008 and 2020 available from Defra projects AQ0815 and AQ0816
- New spatial data for silver-birch and needle-leaf tree flux for 2006, 2007, 2008 and 2020 (would need to be modelled by AEA using OSRM or CEH using EMEP4UK)
- Response function for effects on whole tree biomass determined as part of EU ECLAIRE project together with tree growth model for extrapolation to mature trees
- Value and proportion for timber, pulp and biomass
- Monte Carlo analysis of uncertainty

4.2.4 Regulating services – C sequestration

4.2.4.1 Nitrogen (medium – large impact) and Sulphur (small-medium), woodlands, 6-12 months

Possible for woodlands using:

- Existing European dose response relationships for N and tree biomass C and forest soil C allocation, coupled with ongoing EU ECLAIRE analysis.
- Effects on soil carbon: NERC UK Soil Observatory project is conducting analysis of spatial and temporal patterns in the Countryside Survey topsoil C data. This should reveal if there is an N and / or acidity (N+S) signal for any habitat in the UK over last 25 years.
- Tree inventory data from Forestry Commission (needs collating)
- Existing N and S spatial data for the historical and future scenarios
- Monte Carlo analysis of uncertainty

4.2.4.2 Ozone (medium impact), woodlands, improved grasslands, 6-12 months

For woodlands:

- Effects on net annual increment could be determined using the approaches described above for timber production, using carbon cost for valuation.
- Effects on soil C could only currently be determined by inference from studies of other modifiers of soil C content (i.e. x% reduction in root growth is equivalent to y% reduction in soil C).
- Monte Carlo analysis of uncertainty

For grasslands:

- Further develop the analysis already conducted under Defra project AQ0815 for low-input grasslands for productive, high input grasslands:
- Distribution data from CS
- Existing 24h mean or new ozone flux (would need to be modelled) spatial data
- Biomass response relationships from PhD study
- Valuation data for C
- Monte Carlo analysis of uncertainty

4.2.5 Regulating services – other greenhouse gases

4.2.5.1 Sulphur impact on Methane emissions (small - medium impact), <6 months

Spatial quantification of impact is possible, building on analysis in previous Defra project NE0117:

- Existing dose response relationship for sulphur suppression of methane emissions.
- Methane emission factors for different vegetation types
- Valuation of methane emitted, as CO_2 equivalents.
- Monte Carlo analysis of uncertainty

4.2.5.2 Ozone impact on Methane emissions (small - medium impact), 6 – 12 months

Spatial quantification of impact requires:

- Collation and analysis of existing data to develop dose response relationship.
- Methane emission factors for different vegetation types
- Valuation of methane emitted, as CO_2 equivalents.
- Monte Carlo analysis of uncertainty

4.2.5.3 Nitrogen impact on N_2O emissions (medium – large impact), 6-12 months

This will be possible once new emission factors for N effects have been agreed as part of Defra GHG projects:

- Emission factors for N_2O currently being developed under Defra GHG reporting project.
- Spatially explicit N deposition at 5 x 5 km resolution (available)
- Valuation of carbon emitted, calculated as CO_2 equivalents.
- Monte Carlo analysis of uncertainty

4.2.6 Regulating services – quality of drinking water

4.2.6.1 Nitrogen (small effect) and acidity (Sulphur and Nitrogen, medium effect) on drinking water quality in the uplands, 6-12 months

An initial study would include:

- UK S and N deposition maps (available)
- Derivation of functions for and new upscaling methods for nitrate, DOC and acidity
- Spatial modelling of sensitive ecosystems (to be done from Acid Waters Monitoring Network/Countryside Survey data)
- Costs for water treatment; health costs for carcinogenic by-products of treatment of high DOC water
- Monte Carlo analysis of uncertainty

Note: More detailed analysis could be conducted in one to two years using results of NERC Macronutrients and EU ECLAIRE modelling.

4.2.7 Cultural services – recreational fishing

4.2.7.1 Nitrogen (medium impact), acidity (Sulphur + Nitrogen)(medium impact), 6-12 months

- UK S and N deposition maps (available)

- Existing dose response functions for effects on wild angling species using data from Norway and Sweden to be further developed.
- Upscaling and spatial modelling of sensitive ecosystems
- Value transfer functions for effects on wild angling
- Monte Carlo analysis of uncertainty

4.2.8 *Cultural services - Appreciation of biodiversity (terrestrial)*

4.2.8.1 Nitrogen (large), 6 – 24 months

Development of additional dose response functions for charismatic and non-charismatic species, and consideration of alternative measures for valuing N impacts on biodiversity:

- Detailed literature search and discussion with European colleagues to obtain data to develop dose response relationships for charismatic, and other non-charismatic species
- N deposition data developed for this project
- Value transfer analysis using Christie et al. (2012) or other studies.
- Monte Carlo analysis of uncertainty

4.2.8.2 Ozone (medium), 6-12 months

Further analysis of Countryside Survey data for the two scenarios as conducted under Defra project AQ0815 using species richness.

- Deriving consistent dose response functions for selected habitat types
- Ozone concentration data (as 24 hr mean) for 1987, 2007, 2020 (already available)
- Value transfer studies (already available, but some work required to separately attribute effects of ozone to changes in species richness)
- Monte Carlo analysis of uncertainty

4.2.9 *Cultural services - Appreciation of biodiversity (aquatic)*

4.2.9.1 Sulphur impacts on aquatic biodiversity (medium), 6-12 months

Calculation of sulphur impacts would require:

- Dose response functions linking acidity and changes to fish, birdlife, invertebrates etc.
- Literature search on value transfer for aquatic organisms
- Monte Carlo analysis of uncertainty

5 WP4. Collated damage costs from Defra air quality valuation studies on ecosystem services.

Collated damage costs from this and previous studies for future pollution scenarios are shown below for nitrogen dioxide, ammonia and sulphur dioxide in Table 16 and for ozone in Table 17, with the detailed assessment of the robustness scores for each service within each report presented in Table 18. Damage costs derived for historical pollution scenarios are shown in Appendix D. The reliability scores represent the degree of spatial analysis of impact and the robustness of the dose response relationships and the overall conceptual impact pathway for each service. Outputs from the more recent reports incorporate the latest methodologies and are therefore most robust. Outputs from the earlier reports need to be updated to reflect these methodological developments, and to incorporate more recent scenario information on pollutant emissions and deposition. A detailed description of the reasons for differences between values for nitrogen impacts in the different reports can be found in section 3.7.8 above.

Damage costs for ammonia in the current study are based on only a 6% change in ammonia emissions, with the subsequent deposition of reduced N compounds subject to many non-linear processes. It is therefore recommended that these damage costs only be used for assessments where ammonia emissions are likely to change by less than 10% from 2007 levels. Additional assessments, including running the pollutant dispersion and deposition models, need to be run for situations where ammonia emissions will increase or decrease greater than 10% of the 2007 values. This may require hypothetical scenarios of up to 50% change in ammonia emissions in order to assess likely impact of large scale emission changes.

For ozone, each report developed the methodology further, but used different ozone metrics. It is established that metrics based on ozone flux are the most appropriate for calculating ozone impact. However, the majority of previous ozone impacts work on which dose-response relationships could be based, use AOT40 or other metrics for ozone. There is therefore a need to decide whether dose response functions should focus purely on emerging data using ozone flux, or whether previous data using other metrics can still be used. Any future assessments of ozone concentrations under different pollution scenarios will need to calculate the appropriate metrics to allow damage costs to be applied (and future assessments of impact on ecosystem services to be run). Since each flux-based metric is unique to the receptor (e.g. Wheat, potatoes, grass), separate ozone flux data will need to be calculated for each metric. One further complication is that ozone is a secondary pollutant. In theory, the impact of ozone can be attributed back to emissions of the source precursor chemicals, for example nitrogen dioxide, and might instead be expressed as a component of the nitrogen dioxide damage cost.

5.1.1 Recommendations for further work

- Update previous valuation studies to incorporate more relevant scenario emissions and deposition data, and to reflect improvements in the methodology for modelling impact, particularly on a spatial basis.

- Conduct specific ammonia emission scenarios to evaluate large-scale change in ammonia emissions (see earlier recommendation in section 3.7.10).

Table 16. Collated damage costs (£ per tonne pollutant emitted in UK) plus uncertainty bounds, from Defra air quality valuation reports, future emissions scenarios for NO_2, NH_3 and SO_2.

Values in black are positive, showing a benefit from decreases in nitrogen dioxide, ammonia or sulphur, values in red are negative, showing a cost due to decreases in nitrogen dioxide, ammonia or sulphur. [1] Defra report NE0117, [2] Defra report AQ0815, [3] Defra report AQ0827, [4] Estimate for more conservative timber calculations from Defra report NE0117. n.v. = Not Valued. Rigour of value estimate: ## Robust, # Acceptable, (#) Improvements desirable and not currently acceptable for policy appraisal.

	Provisioning Services			*Regulating Services*				*Cultural Services*	
				Net GHG emissions					
	Crop production	Timber production[4]	Livestock production	CO_2	N_2O	CH_4	Clean water	Recreational fishing	Appreciation of biodiversity
Decreasing Nitrogen dioxide	n.v.	-£4.3 (-£8.0 to -£2.3)[1] (#)	-£8.8 (-£11.8 to -£5.6)[1] (#)	-£54.0 (-£94.0 to -£22.8)[1] #	£11.8 (£6.2 to £18.7)[1] #	n.v.	n.v.	£0.1 (uncertainty not calculated)[1] (#)	£77.6 (£11.1 to £141.2)[1] (#) £102.8 (£33.3 to £237.4)[3] ##
Decreasing Ammonia	n.v.	-£93.1 (-£170.7 to -£49.7)[1] (#)	-£294.1 (-£395.9 to -£186.6)[1] (#)	-£1,267.1 (-£2,204.0 to -£535.4)[1] #	£338.4 (£179.1 to £537.4)[1] #	n.v.	n.v.	£2.2 (uncertainty not calculated)[1] (#)	£2,559.4 (£364.3 to £4,792.8)[1] (#) (£413.8) (£139.1 to £1,021.5)[3] ##
Decreasing Sulphur dioxide	n.v.	n.v.	n.v.	n.v.	n.v.	-£5.3 (-£1.6 to -£9.5)[1] #	n.v.	n.v.	n.v.

Table 17. Collated damage costs (£ per unit ozone) plus uncertainty bounds, from Defra air quality valuation reports, future emissions scenarios.

Values in red are negative, showing a cost due to increases in ozone. [1] Defra report NE0117, [2] Defra report AQ0815, [3] Defra report AQ0827. n.v. = Not Valued. Rigour of value estimate: ## Robust, # Acceptable, (#) Improvements desirable and not currently acceptable for policy appraisal.

	Provisioning Services			*Regulating Services*				*Cultural Services*	
				Net GHG emissions					
	Crop production	**Timber production**	**Livestock production**	CO_2	N_2O	CH_4	**Clean water**	**Recreational fishing**	**Appreciation of biodiversity**
Increasing Ozone per unit 6-month AOT40 (ppmh)	n.v.	-£550,000 (-£297,000 to -£837,000)[1] (#)	n.v.	-£11,959,000 (-£7,560,000 to -£16,346,000)[1] (#)	n.v.	n.v.	n.v.	n.v.	n.v.
Increasing Ozone per unit 7-month 24-hr mean (ppb)	n.v.	n.v.	-£1,051,000 (-£1,705,000 to -£427,000)[2] ##	-£5,740,000 (-£7,939,000 to -£3,866,000)[2] ##	n.v.	n.v.	n.v.	n.v.	n.v.
Increasing Ozone per unit flux (POD)	-£100,555,000 (-£118,970,000 to -£83,421,000)[3] ##	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.	n.v.

Table 18. Assessment of robustness of Damage Cost figures for ecosystem services, collated from Defra air quality valuation reports.
Shaded boxes indicate limitations of current calculations. Those with robustness score '(#) – Improvements desirable' are not considered sufficiently robust for policy appraisal at present.

Pollutant	Ecosystem Service	Defra report/ Reference	Scope/ habitats covered	Impact pathway	Response functions	Spatial method-ology	Valuation	Robust-ness score	Notes
Nitrogen	Timber production	NE0117	Woodland (softwood, hardwood)	Improvements desirable	Acceptable, based on meta-analysis	No	Improvements desirable	(#)	Could utilise tree growth model
	Livestock production	NE0117	Improved grassland	Improvements desirable	Acceptable	No	Improvements desirable	(#)	Needs input from agricultural economists
	Net GHG emissions (CO2)	NE0117	Woodland, Heathland	Acceptable	Acceptable	No	Robust	#	Could utilise tree growth model
	Net GHG emissions (N2O)	NE0117	All semi-natural habitats	Acceptable	Acceptable	No, but spatial analysis unlikely to add much	Robust	#	May need updating to reflect ongoing GHG reporting
	Recreational fishing	NE0117	Upland rivers	Improvements desirable	Improvements desirable	No	Acceptable	(#)	Improve upscaling to UK
	Appreciation of biodiversity	NE0117	Woodland, Heathland, Acid grassland, Calcareous grassland, Bog	Acceptable	Improvements desirable	No	Improvements desirable	(#)	Improve response functions, spatial methodology, and value transfer
		AQ0827	Heathland, Acid grassland, Dune grassland, Bog	Robust	Robust, based on careful survey design for 4 habitats	Yes	Acceptable	##	Only covers 4 habitats, and non-charismatic species. Additional valuation may be possible.

Pollutant	Ecosystem Service	Defra report/ Reference	Scope/ habitats covered	Impact pathway	Response functions	Spatial method-ology	Valuation	Robust-ness score	Notes
Sulphur	Net GHG emissions (CH4)	NE0117	Bog	Acceptable, but more data on typical CH4 emissions desirable	Acceptable, based on meta-analysis	No	Robust	#	
Ozone	Wheat production	AQ0827	Wheat cropland	Robust	Robust, based on meta-analysis.	Yes	Robust	##	Ozone metric: Flux-based POD_6wheat.
	Timber production	NE0117	Woodland (softwood, hardwood)	Improvements desirable	Acceptable, based on meta-analysis	No	Improvements desirable	(#)	Ozone metric: AOT40. Could utilise tree growth model
	Lamb production	AQ0815	Upland and lowland lamb production	Robust	Acceptable, based on meta-analysis.	Yes	Robust	##	Ozone metric: 7-month growing season 24hr mean ozone.
	Net GHG emissions (CO2)	NE0117	Woodland, Grassland	Improvements desirable	Acceptable for woodland; Improvements desirable for grassland (based on single study).	No	Improvements desirable	(#)	Ozone metric: AOT40. Majority of value due to grassland impact which needs improvement
		AQ0815	Grassland	Robust	Robust, based on meta-analysis.	Yes	Robust	##	Ozone metric: 7-month growing season 24hr mean ozone.

Robust, # Acceptable, (#) Improvements desirable. n.v. = Not Valued.

6 Conclusions and overall recommendations.

Recent Defra-funded projects have made considerable improvements in the methodology of valuing air pollution impacts on ecosystem services, particularly the spatially explicit calculation of air pollution impact and uncertainty analysis of the results. This study has built on these developments to further improve the methodology for air pollution impacts on two ecosystem services: To improve the spatial analysis of impact and value transfer approach for nitrogen impacts on ‘appreciation of biodiversity’, and to apply the marginal cost approach to ozone impacts on wheat production.

The gap analysis collated information about ongoing initiatives and data sources which might lead to further advances in the modelling of air pollution impacts on ecosystem services in the next few years. Based on the expert knowledge of members of the consortium, the potential magnitude, the impact pathway and timescale to achieve valuation of impacts of air pollutants on each ecosystem service was assessed. From this assessment, two further services were identified that could be valued in < 6 months:

-Valuing ozone impact on 2 crops (potato, oilseed rape) (Medium impact)
-Valuing sulphur impact on methane emissions (Small-Medium impact)

Valuation work would be possible on 19 other services in a timescale of 6-24 months.

This report also collated damage costs from previous study and evaluates their robustness for policy appraisal. Reliability scores were assigned based on robustness of the impact pathway and dose-response functions, and the ability to model impact spatially. Although not all previous damage costs were based on spatial calculation of impact, some are considered robust enough for use in policy appraisal although they should be brought to the standard of the current methodology when the chance arises. Others however are not sufficiently reliable at present and require improvements in dose-response functions or valuation, as well as spatial calculation of impact before they can be used (Table 18). Where damage costs are considered sufficiently robust, the following recommendations are made:

- The damage costs for ozone can be used in policy appraisal, however further discussion is needed on how to calculate damage costs for ozone as a secondary pollutant. Although ozone flux is the most scientifically accurate method currently available for valuation of effects related to vegetation, the possibility of using other ozone metrics, or relating damage directly to emissions of precursor chemicals could be explored.

- In order to calculate flux-based damage costs for ozone in new policy situations, the relevant flux-based measures (e.g. POD_6wheat) need to be calculated for each scenario.

- The damage costs for nitrogen dioxide can be used in policy appraisal, since they reflect the result of large declines in emission and in deposition of oxidised N in the scenario evaluated.

- It is only recommended to use the damage costs for ammonia in policy appraisal where changes in emissions of reduced N are less than 10%. Relationships between N emission and deposition are non-linear and the scenario used here was based on only a 6% decline in emissions of reduced N. Therefore application to larger emission changes is not recommended.

- The damage costs for impacts on ‘appreciation of biodiversity’ can be applied for increases or decreases in N emissions.

Reporting under individual work packages identifies a number of recommendations. In addition we make a number of further high-level recommendations. Further work should aim to:

- Update the calculations and damage costs for previously valued services using the latest methodology. This should incorporate more recent scenario emissions and deposition, and spatial analysis of impact on ecosystem services.
- Construct and run meaningful scenarios for large-scale changes in ammonia emissions, because damage costs for NH_3 developed under the current scenario should only be applied where emission changes are < 10%. This will involve running the full impact pathway, including dispersion and deposition models, calculating impacts on ecosystem services and conducting uncertainty analysis for a range of services.
- Improve valuation of air pollution impacts on cultural services and regulating services where pollution has an adverse impact, using the horizon scanning to prioritise.

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Appendix A. Summary tables from gap-analysis workshop (WP1)

Summary of available evidence and methods for valuing air pollution impacts on Ecosystem Services. Workshop (Task WP1.1), held 29th April 2013, CEH Bangor.

Crop production– Nitrogen

Crop production - Nitrogen	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduced crop growth due to falling nitrogen deposition** Falling N deposition leads to reduced yield of biomass crops (which have low fertiliser applications)	**Reduced value of crops** Reduced crop yield leads to reduced value to farmers
Measure of Impact	Change in crop yield (e.g. Miscanthus, Willow)	Change in value of crops
Data sources	Crop yield Nitrogen requirement of crops	Farm gate price of crops Cost of nitrogen fertiliser
Methodology	-Calculate difference in yield due to falling nitrogen deposition	-Calculate value of difference in yield OR -Calculate cost of fertiliser required to offset reduction in yield OR -Because these crops not yet widespread, show proportional change in yield for all areas in UK where these crops could be grown
Assumptions		Farmers notice change in yield and compensate with fertiliser
Dose-response functions available	Not yet available	
How apply spatially?	-Calculate change in yield for each grid cell where biomass crops are grown (if we know where the crops are grown). -Upscale based on crop area in the grid cell	Sum to UK level
Potential sources of new information		

Crop production– Sulphur

Crop production - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduced crop growth due to falling suphur deposition** Falling S deposition leads to reduced yield of certain crops (some have very high S demand)	**Reduced value of crops** Reduced crop yield leads to reduced value to farmers
Measure of Impact	Change in crop yield	Change in value of crops
Data sources	Crop yield Sulphur requirement of crops Soil type?	Farm gate price of crops Cost of sulphur fertiliser
Methodology	-Calculate difference in yield due to falling sulphur deposition	-Calculate value of difference in yield OR -Calculate cost of fertiliser required to offset reduction in yield
Assumptions		Farmers notice change in yield and compensate with fertiliser
Dose-response functions available	Not yet available	
How apply spatially?	-Calculate change in yield for each grid cell where relevant crops are grown -Upscale based on crop area in the grid cell	Sum to UK level
Potential sources of new information		

Crop production– Ozone

Crop production - Ozone	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Ozone toxicity damage** Increasing ozone concentrations leads to reduced crop growth and yields and reduced yield quality	**Reduced value of crops** Reduced crop yield leads to reduced value to farmers
Measure of Impact	Change in crop yield (wheat, potato)	Change in value of crops
Data sources	Crop yield	Farm gate price of crops
Methodology	(Approach in Mills et al. 2011) -Model difference in yield under current ozone compared with reference state assuming no ozone-induced reduction in yield . For UK 2006 (potential future year) compared so far with 2008 (more usual year). Mean of 13 years farm gate crops process used for valuation (Potential approach consistent with other services in this study) #1 Flux-based method -Average spatial pattern for years available, project to 2020 (Potential approach consistent with other services in this study) #2 using 24hr mean ozone -Average spatial pattern using 5-yr averages for periods 1987, 2007, 2020	-Calculate value of difference in yield Note: a marginal cost approach could be used but care would need to be taken because of the fluctuating prices of crops
Assumptions	Linear change in ozone concentration/flux between reference years used in scenarios	- Use 13 yr average crop price -? Use multi-year average of yield
Dose-response functions available	Dose response functions for wheat, potato and oilseed rape using flux-based relationships.	

Crop production - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
How apply spatially?	-Calculate change in yield for each grid cell. Flux data available for 2006, 2007, 2008 and 2020	Sum to UK level
Potential sources of new information	EMEP4UK model, may be able to provide flux data for wider range of dates.	

Livestock production – Nitrogen

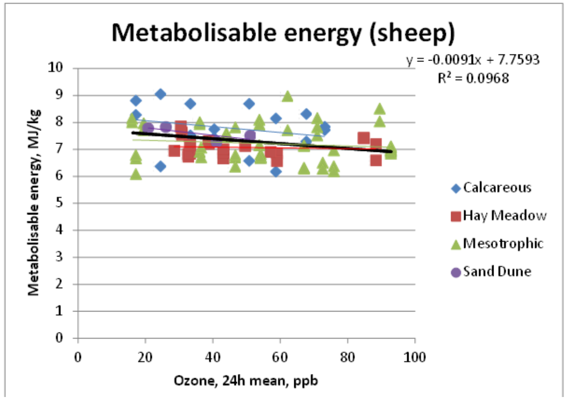
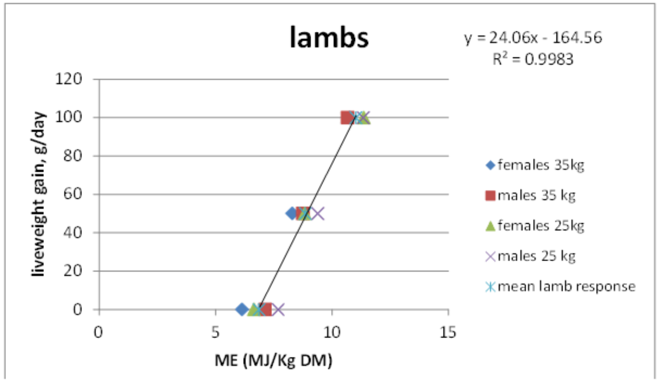
Livestock production - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in free fertiliser effect of nitrogen** Decreasing N deposition leads to reduced pasture yield	**Reduced value of livestock products** Reduced livestock growth leads to reduction in sale value, or additional feed costs for farmers
Measure of Impact	Change in livestock growth rates	Change in UK value of livestock/livestock products
Data sources	Need detailed knowledge of animal production systems, including feed requirements of stock	Fertiliser cost prices Farm gate prices
Methodology	-Model difference in N input (kg/ha/yr) that is required to be replaced with fertiliser, for improved grassland only -Unimproved grassland may require calculations of change in liveweight gain	-Calculate cost of additional fertiliser OR -Calculate change in price of feed crops, or change in milk/beef yield assuming no compensation by farmers
Assumptions	-Various assumptions involving how animal production methods would respond	-Farmers notice change in yield (actually very small) and compensate through additional fertiliser, or supplementary feed
Dose-response	Not yet available	
How apply spatially?	-Calculate change in N deposition/pasture or crop yield for each grid cell in which improved grassland, or feedcrops occur.	Sum to UK level
Potential sources of new information		

Livestock production – Sulphur

Livestock production - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in free fertiliser effect of sulphur** Decreasing sulphur deposition leads to reduced pasture yield	**Reduced value of livestock products** Reduced livestock growth leads to reduction in sale value, or additional feed costs for farmers
Measure of Impact	Change in livestock growth rates	Change in UK value of livestock/livestock products
Data sources	Need detailed knowledge of animal production systems, including feed requirements of stock	Fertiliser cost prices Farm gate prices
Methodology	-Model difference in sulphur input (kg/ha/yr) that is required to be replaced with fertiliser, for improved grassland only -Unimproved grassland may require calculations of change in liveweight gain	-Calculate cost of additional fertiliser OR -Calculate change in price of feed crops, or change in mild/beef yield assuming no compensation by farmers
Assumptions	-Various assumptions involving how animal production methods would respond	-Farmers notice change in yield (likely to be small) and compensate through additional fertiliser, or supplementary feed
Dose-response	Not yet available	
How apply spatially?	-Calculate change in sulphur deposition/pasture or crop yield for each grid cell in which improved grassland, or feedcrops occur.	Sum to UK level
Potential sources of new information		

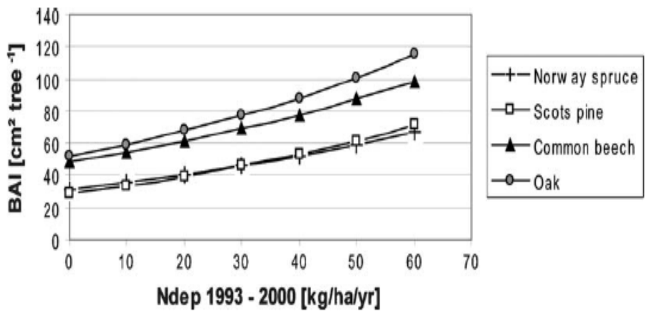
Livestock production – Ozone

Livestock production - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Ozone toxicity damage** Increasing ozone concentrations lead to reduced pasture yield and nutritional quality	**Reduced value of livestock products** Reduced livestock growth leads to reduction in sale value, or additional feed costs for farmers
Measure of Impact	Change in livestock growth rates (lambs only, other livestock possible)	Change in UK value of livestock/livestock products
Data sources	Livestock density/numbers	Market prices of livestock Feed cost prices
Methodology	Cattle: Methodology needs further development -grass-based systems -dairy (fed grass/silage, and feed crops usu. maize) -indoor systems (feed) Lambs: -Model difference in growth rates (live weight gain) under ozone based on impacts on Metabolisable Energy (ME) of pasture (derived from forage yield and quality)	Lambs: -Calculate cost of concentrate required to make up difference in yield (more robust methodology than assuming farmers sell livestock at lower weights)
Assumptions	-	- 50% of upland lambs sold for consumption - 80% of lowland lambs sold for consumption -Farmers respond to changes in liveweight gain with supplementary feed
Dose-response	Ozone vs ME; ME vs live weight gain	

Livestock production - Ozone	Ecosystem Response	Ecosystem Service, and Valuation
	 	
How apply spatially?	-Calculate change in live-weight gain, and therefore supplementary concentrate required for each grid cell, scaling by livestock numbers	
Potential sources of new information	-Current experiments at CEH Bangor may provide dose-response function for ozone impacts on quality of improved grasslands	

Timber production – Nitrogen

Timber production - Nitrogen	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in growth stimulation due to nitrogen** Decreasing N deposition leads to reduced tree growth. Some disagreement on evidence for this in the UK	**Reduced value of timber** Reduced tree growth leads to reduction in sale value for timber
Measure of Impact	Change in tree growth/tree biomass	Change in value of timber production
Data sources	-Which species are grown where in UK -Spatial information on yield/growth rates (unit growth rates and/or volume of production)	Timber production Timber sale prices
Methodology	-Model difference in stem increment due to N deposition, separately for deciduous and coniferous species • Ratio of carbon sequestrated per unit of N ranges from 15 - 40 kg C per kg N for increases in N deposition. • Ratio of carbon sequestrated per unit of N ranges from 2.3 - 16 kg C per kg N for decreases in N deposition. • Proportion of wood that is carbon is 0.5.	-Convert changes in stem increment to quantities of timber sold • Conversion of green wood volume to dry wood (timber) - range of 0.33 – 0.53 t/m^3 across softwoods and hardwoods. 0.45t/m^3 is applied for both. • Aggregate change in timber produced per hectare over total area (hectares) for softwood and hardwood production. • 2 different approaches to estimate actual production of softwood/hardwood in Private Woodland and Public Estate
Assumptions	-Response to recovery is smaller than that for additional N (based on Wamelink et al. 2009) -Response functions based on Europe-wide data are valid for UK	-Various assumptions required in upscaling change in tree growth to actual timber harvested -Assumes foresters don't change rotation length or other management in response to N
Dose-response		

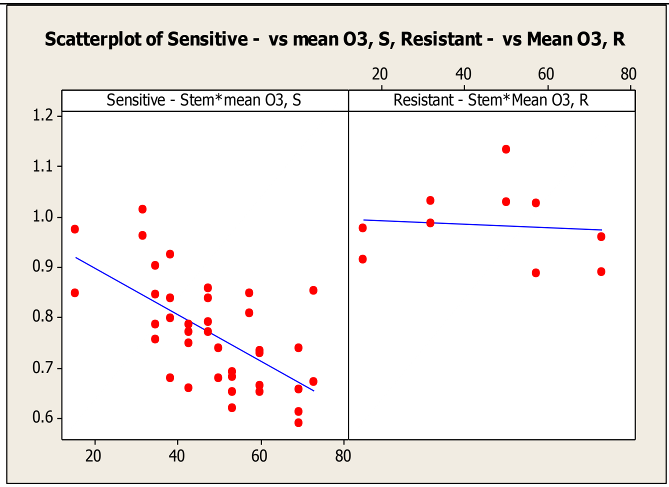
Timber production - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
		
How apply spatially?	-Calculate change in tree growth within each grid cell in which each woodland type occurs.	Upscale impacts based on spatially explicit production data
Potential sources of new information	Input required from foresters with forest-growth models (CARBINE model) Possible influence of disease/pest outbreaks and interactions with air pollution	

Timber production – Sulphur

Timber production - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in growth stimulation due to sulphur** At current levels of sulphur deposition, impacts are likely to be due to sulphur deficiency, rather than acute sulphur toxicity	**Reduced value of timber** Reduced tree growth leads to reduction in sale value for timber
Measure of Impact	Change in tree growth/tree biomass	Change in value of timber production
Data sources	-Sulphur impacts assumed negligible at European scale. -Very little UK evidence	Timber production Timber sale prices
Methodology		
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information		

Timber production – Ozone

Timber production - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in tree growth due to ozone** Increasing ozone leads to reduced tree growth	**Reduced value of timber** Reduced tree growth leads to reduction in sale value for timber
Measure of Impact	Tree growth/tree biomass	Change in value of timber production
Data sources	-Which species are grown where in UK -Spatial information on yield/growth rates (unit growth rates and/or volume of production)	Timber volume and increment by species, age class and region (National Forest Inventory data) Timber sale prices
Methodology	-Model difference in stem increment due to ozone, separately for deciduous and coniferous species For Sensitive spp (Betula pendula, Corylus avellana, Quercus robur) y=-0.0047756, $p<0.001$) For Resistant spp (Alnus glutinosa, Fagus sylvatica) Y=-0.000362, p=n.s. Proportionally weighted slopes based on area of those spp (NEA Forestry chapter) • Y=-0.00392	-Convert changes in stem increment to quantities of timber sold • Conversion of green wood volume to dry wood (timber) – range of 0.33 – 0.53 t/m^3 across softwoods and hardwoods. 0.45t/m^3 is applied for both. • Aggregate change in timber produced per hectare over total area (hectares) for softwood and hardwood production.
Assumptions	-	-Various assumptions required in upscaling change in tree growth to actual timber harvested -Assumes foresters don't change rotation length or other management in response to ozone
Dose-response	Response function for broadleaved species	

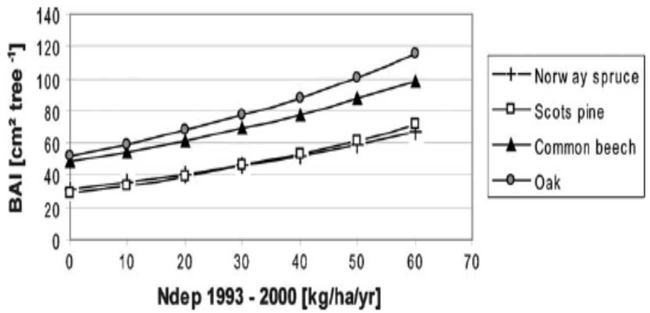
Timber production - Ozone	**Ecosystem Response**	**Ecosystem Service, and Valuation**
	 Response functions also available for conifers	
How apply spatially?	-Calculate change in tree growth within each grid cell in which each woodland type occurs.	Upscale impacts based on spatially explicit production data
Potential sources of new information	Input required from foresters with forest-growth models Possible influence of disease/pest outbreaks and interactions with air pollution	

Water Supply –Nitrogen, Sulphur, Ozone

Water supply - **Nitrogen, Sulphur, Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Altered quantity of water supplied to rivers, lakes or reservoirs.** Possible links identified between pollutants and water supply: -Decreased plant growth due to declining **nitrogen** may result in greater water supply (through lower ET losses) -Decreased plant growth due to declining **sulphur** may result in greater water supply (through lower ET losses) -Altered water retention characteristics of peat due to **sulphur, or nitrogen** deposition may affect water supply -Reduced plant growth due to increasing **ozone** may result in greater water supply (through lower ET losses).	**Altered value of water** Altered water supply
Measure of Impact	Change in water supply	Change in value of water supply
Data sources		OECD has a publication on the benefits of water supply.
Methodology		
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information		

Carbon sequestration – Nitrogen

Carbon sequestration - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Changes in carbon sequestration due to declining nitrogen deposition** Decreasing N deposition leads to changes in plant growth and therefore carbon sequestration in biomass and soils. Responses are habitat specific: Decreases in C in woodlands, heathlands, grasslands, more complex response in bogs	**Reduced value of CO2 sequestration** Reduced carbon allocation to biomass and soils leads to decrease in value of carbon sequestration service
Measure of Impact	-Tree growth/tree biomass -Plant growth	- Change in value of carbon sequestration
Data sources	Woodlands: -Which tree species are grown where in UK -Spatial information on yield/growth rates (unit growth rates and/or volume of production) Heathlands, Grasslands, Bogs: Current growth rates (NPP appropriate for grasslands only)	Carbon sequestered (via changes in timber). Timber volume and increment by species, age class and region (National Forest Inventory data) Shadow price of carbon
Methodology	Woodlands: -Model difference in stem increment due to N deposition, separately for deciduous and coniferous species • Ratio of carbon sequestrated per unit of N ranges from 15 - 40 kg C per kg N for increases in N deposition. • Ratio of carbon sequestrated per unit of N ranges from 2.3 - 16 kg C per kg N for decreases in N deposition. • Proportion of wood that is carbon is 0.5. Heathlands, Bogs: Needs further work Grasslands: Based on NPP	-Convert changes in tree or plant growth to quantities of carbon sequestered -Calculate long-term carbon sequestration into soils

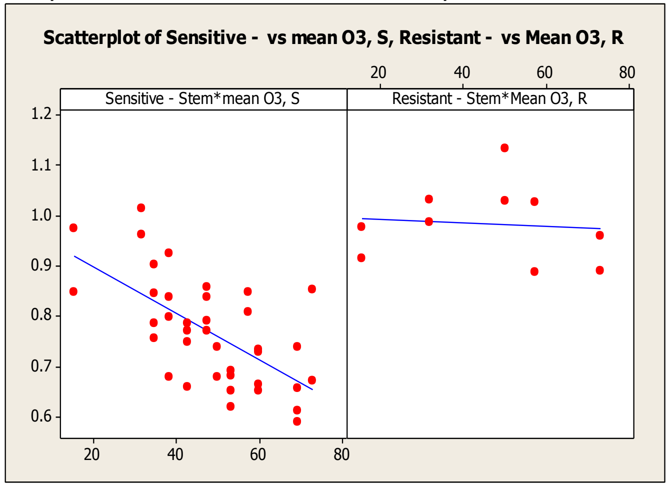
Carbon sequestration - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Assumptions	Woodlands: -Response to recovery is smaller than that for additional N (based on Wamelink et al. 2009) -Response functions based on Europe-wide data are valid for UK	-Various assumptions required in upscaling change in tree growth to actual timber harvested -Assumes foresters don't change rotation length or other management in response to N
Dose-response	Woodlands:  Other habitats: More synthesis required	
How apply spatially?	-Calculate change in plant growth within each grid cell for relevant habitats.	Upscale impacts based on spatially explicit production data (woodlands). Other habitats need further work.
Potential sources of new information	-Input required from foresters with forest-growth models -Possible influence of disease/pest outbreaks and interactions with air pollution -New synthesis required for some habitats	

Carbon sequestration – Sulphur

Carbon sequestration - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in growth stimulation due to sulphur** At current levels of sulphur deposition, impacts are likely to be due to sulphur deficiency, rather than acute sulphur toxicity	**Reduced value of CO2 sequestration** Reduced carbon allocation to biomass and soils leads to decrease in value of carbon sequestration service
Measure of Impact	-Tree growth/tree biomass -Plant growth	- Change in value of carbon sequestration
Data sources	-Sulphur impacts on woodland assumed negligible at European scale. -Very little UK evidence for impacts on other habitats	
Methodology		
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information		

Carbon sequestration – Ozone

Carbon sequestration - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Reduction in carbon sequestration due to ozone** Increasing ozone leads to reduced tree growth and therefore reduced carbon sequestration in biomass and soils	**Reduced value of CO_2 sequestration** Reduced tree growth leads to reduction in total carbon sequestered (and its value)
Measure of Impact	-Tree growth/tree biomass -Plant growth	- Change in value of carbon sequestration
Data sources	Woodlands: -Which tree species are grown where in UK -Spatial information on yield/growth rates (unit growth rates and/or volume of production) Heathlands, Grasslands, Bogs: Current growth rates (NPP appropriate for grasslands only)	Carbon sequestered (via changes in timber). Timber volume and increment by species, age class and region (National Forest Inventory data) Shadow price of carbon
Methodology	Woodlands: -Model difference in stem increment due to ozone, separately for deciduous and coniferous species For Sensitive spp (Betula pendula, Corylus avellana, Quercus robur) y=-0.0047756, p<0.001) For Resistant spp (Alnus glutinosa, Fagus sylvatica) Y=-0.000362, p=n.s. Proportionally weighted slopes based on area of those spp (NEA Forestry chapter) • Y=-0.00392 Other habitats: NPP for grasslands, methodology for heathlands etc, not developed yet	-Convert changes in tree or plant growth to quantities of carbon sequestered -Calculate long-term carbon sequestration into soils
Assumptions	-	-Various assumptions required in upscaling change in tree growth to actual timber harvested

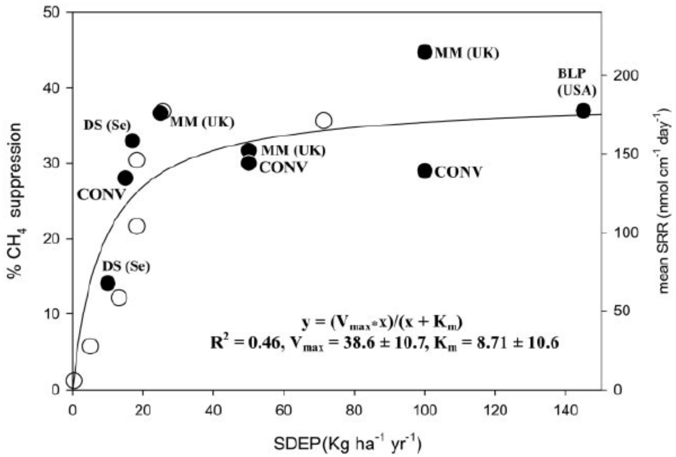
<table>
<tr><th>Carbon sequestration
- Ozone</th><th>Ecosystem Response</th><th>Ecosystem Service, and Valuation</th></tr>
<tr><td></td><td></td><td>-Assumes foresters don't change rotation length or other management in response to ozone</td></tr>
<tr><td>Dose-response</td><td>Response function for broadleaved species


Response functions available for coniferous trees and for grasslands.</td><td></td></tr>
<tr><td>How apply spatially?</td><td>-Calculate change in plant growth within each grid cell for relevant habitats.</td><td>Upscale impacts based on spatially explicit production data (woodlands).
Other habitats need further work.</td></tr>
<tr><td>Potential sources of new information</td><td>-Input required from foresters with forest-growth models
-Possible influence of disease/pest outbreaks and interactions with air pollution
-New synthesis required for some habitats</td><td></td></tr>
</table>

Methane emissions – Nitrogen

Methane emissions - Nitrogen	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Change in methane emissions due to nitrogen** Nitrogen may drive changes in methane emissions, via changes in vegetation community composition, from moss dominated to sedge dominated (Indirect effect)	**Changed value of CO2 equivalent** Change in climate forcing
Measure of Impact	Change in methane emissions	Change in climate forcing, measured as CO2equivalents of methane
Data sources	No concensus currently on impact of nitrogen on methane. Little or no evidence for community change N.B. Possible link to agricultural methane emissions, either through change in animal nutrient intake, or longer duration of animals on pasture	
Methodology		
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information		

Methane emissions – Sulphur

Methane emissions - Sulphur	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Increase in methane emissions due to lower sulphur deposition** Reduction in sulphur deposition releases microbial controls on methane production	**Increased climate forcing due to methane** Increased methane production leads to increased climate forcing
Measure of Impact	Change in methane emissions	Change in climate forcing, measured as CO2equivalents of methane
Data sources	Current rates of methane emissions, spatially	Shadow price of carbon
Methodology	Calculate change in methane emissions due to change in sulphur. (Use vegetation type as proxy for condition and therefore methane emissions from bogs)	Convert to Global Warming Potential using CO2 equivalents
Assumptions	Doesn’t take account of stored sulphur in soils (may not be an issue)	
Dose-response	From Gauci et al. (2004) 	
How apply spatially?	Calculate at 1x1km resolution in locations where bogs occur	
Potential sources of new information	VNN Peatlands: (see Chris Evans), also submitted paper by Martin-Ortega	

Methane emissions – Ozone

Methane emissions - Ozone	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Change in methane emissions due to ozone** Ozone may drive changes in methane emissions, via changes in vegetation community composition or directly via changes in plant growth	**Changed value of CO2 equivalent** Change in climate forcing
Measure of Impact	Change in methane emissions	Change in climate forcing, measured as CO2equivalents of methane
Data sources	No concensus currently on impact of ozone on methane.	
Methodology		
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information	Submitted paper by Williamson et al. shows possible uni-modal relationship with ozone	

Nitrous oxide emissions – Nitrogen

Nitrous oxide emissions - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Increase in N2O emissions due to N deposition** Reduction in N deposition leads to lower N2O emissions	**Decreased climate forcing due to N2O** Decreased N2O emission leads to decreased climate forcing
Measure of Impact	Change in N2O emissions	Change in climate forcing, measured as CO2equivalents of N2O
Data sources	-N deposition -(Soil type)	Shadow price of carbon
Methodology	Calculate change in N2O emissions due to change in N deposition	Convert to Global Warming Potential using CO2 equivalents
Assumptions	-Currently same emission rates for all habitats	
Dose-response		
How apply spatially?	Calculate at 1x1km resolution across UK	
Potential sources of new information	Forthcoming study on GHG emissions aims to develop emission factors for different soil types	

Quality of water for drinking – Nitrogen

Quality of water for drinking. - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Eutrophication of drinking water** Increasing N deposition leads to elevated nitrate concentrations in surface waters and groundwater.	**Reduced quality of water for drinking** Health risks associated with high nitrate concentrations. Therefore a cost to water companies to reduce nitrate concentrations in drinking water.
Measure of Impact	Change in nitrate concentrations in surface waters in water catchments	Change in treatment costs to remove nitrates
Data sources	Surfacewater quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models Groundwater quality -EA data?	-Ongoing treatment costs (check with water companies)
Methodology	-Model atmospheric N contribution to nitrate in freshwater in uplands. N.B. Atmospheric input of N only likely to be significant where agricultural terrestrial sources are low, i.e. the unimproved uplands.	-
Assumptions	-We can separate out atmospheric contribution to nitrate in waters.	-Treatment costs are a function of nitrate concentrations. -We can disaggregate costs required for removal of nitrate
Dose-response		
How apply spatially?	-Upscale to all upland catchments	
Potential sources of new information	Need to contact upland water companies to see if there is an impact	

Quality of water for drinking – Sulphur

Quality of water for drinking. - **Sulphur**	**Ecosystem Response**	**Valuation**
Impact, and mechanism	**Acidity-related impacts on drinking water** Falling sulphur deposition leads to an increase in dissolved organic carbon (DOC) concentrations in surface waters. Possible links to metal toxicity linked to changes in acidification. Possible links also to suspended solids in water due to peat breakdown	**Reduced quality of water for drinking** DOC represents a potential health risk and customers dislike brown water. Therefore a cost to water companies to reduce DOC concentrations in drinking water.
Measure of Impact	Change in DOC concentrations in surface waters.	Change in treatment costs to remove DOC
Data sources	Water quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models	-Infrastructure costs over the scenario lifetime? -Ongoing treatment costs
Methodology	-Model DOC concentrations in freshwater in response to falling Sulphur deposition. N.B. Note potential links to metal release due to acidity, and suspended solids in water due to peat breakdown.	-
Assumptions	-No lags in response of DOC to changing S deposition.	-Treatment costs are related to DOC concentrations.
Dose-response		
How apply spatially?	-Upscale to all upland catchments	
Potential sources of new information	-VNN Peatlands may have synthesised valuation evidence (Martin-Ortega paper submitted) -Ed Tipping (CEH) study on metal release due to acidity	

Recreational fishing – Nitrogen

Recreational Fishing. - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Eutrophication of rivers and lakes** Increasing N deposition contributes to aquatic eutrophication and leads to reduced fish abundance and diversity in rivers and lakes. Mainly relevant for wild river fishing.	**Reduced catch of fish by recreational fishermen** Reduced catch or degraded visual appearance of rivers lead to fewer recreational fishing visits (wild river fishing).
Measure of Impact	Nitrate concentrations Fish abundance and diversity	Number of fishing visits
Data sources	Water quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models Fish abundance/diversity -EA data N.B. Lowland stocked fisheries now moving to fish such as carp, which may prefer eutrophic rivers and contribute to eutrophication through feeding behaviour.	-Trip generator model (Johnston and Markandya 2006) N.B. May not be relevant for wild rivers
Methodology	-Model atmospheric N contribution to nitrate in freshwater using ? FAB model. Only apply in uplands to wild rivers. -Model changes in fish population to nitrate concentrations Or: -Model changes in fish populations directly to N deposition	-Link fishing visits to nitrate concentrations using trip generator model
Assumptions	-We can separate out atmospheric contribution to nitrate in waters. -Fish populations respond to nitrate concentrations, given other known factors (e.g. Phosphorus load)	-That rivers are not substitutable -Fishing occurs in, and is responsive to condition in affected rivers
Dose-response		
How apply spatially?	-Upscaling to all relevant rivers -Relevant spatial scale for modelling	Apply value uniformly across UK in absence of other information.
Potential sources of new information		

Recreational fishing – Sulphur

Recreational Fishing. - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Acidification of rivers and lakes** Increasing S deposition contributes to acidification of rivers and lakes and leads to reduced fish abundance and diversity.	**Reduced catch of fish by recreational fishermen** Reduced fish abundance leads to fewer recreational fishing visits.
Measure of Impact	Change in ANC or pH of freshwaters Change in fish abundance and diversity	Change in number of fishing visits
Data sources	Water quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models -Known thresholds for ANC for salmonids Fish abundance/diversity -EA data	-
Methodology	-Model atmospheric S contribution to pH or ANC concentrations in acid-sensitive freshwaters -Model changes in fish population to pH, ANC concentrations. Or: -Model changes in fish populations directly to S deposition	-Link fishing visits to fish abundance
Assumptions	-We can separate out atmospheric contribution to acidity in waters.	-That rivers are not substitutable -Fishing occurs in, and is responsive to condition in affected rivers
Dose-response		
How apply spatially?	-Upscaling to all relevant rivers -Relevant spatial scale for modelling	
Potential sources of new information		

Appreciation of biodiversity (aquatic) – Nitrogen

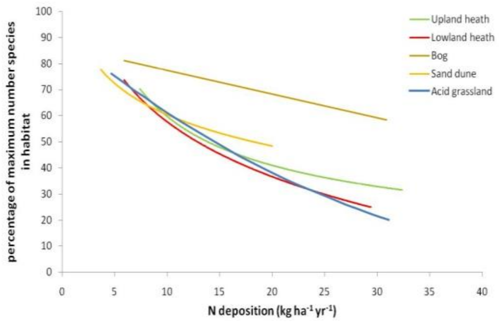
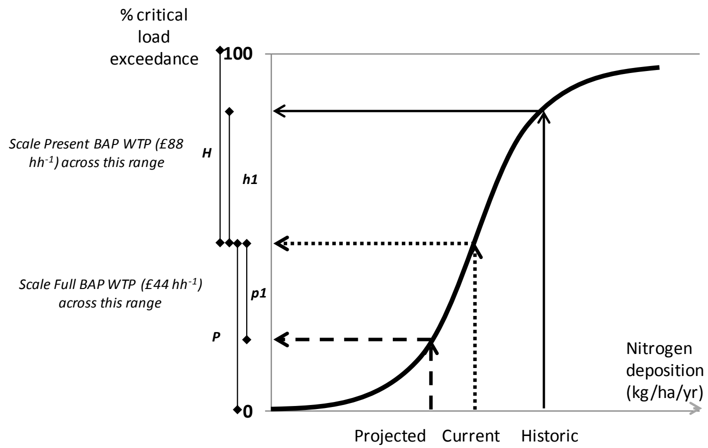
Appreciation of biodiversity (aquatic). - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Eutrophication of rivers and lakes** Increasing N deposition contributes to aquatic eutrophication and leads to reduced abundance and diversity of aquatic life (fish, invertebrates, birds) in rivers and lakes.	**Reduced appreciation of aquatic biodiversity** Reduced fish abundance and degraded visual appearance of rivers lead to reduction in biodiversity value.
Measure of Impact	-Change in nitrate concentrations -Abundance and diversity of fish and/or other organisms	Change in WTP to maintain biodiversity Change in value of rivers
Data sources	Water quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models Fish abundance/diversity (as proxy for wider aquatic biodiversity) -EA data -invertebrate abundance indices (e.g. RIVPACS)	-WTP to maintain abundance of fish or aquatic species ? (Christie et al. 2010) -Other studies are available on aquatic biodiversity
Methodology	-Model atmospheric N contribution to nitrate in freshwater using FAB model. -Model changes in fish population/other organisms to nitrate concentrations Or: -Model changes in fish populations/other organisms directly to N deposition	-Link WTP to abundance/diversity of aquatic organisms
Assumptions	-We can separate out atmospheric contribution to nitrate in waters. -Fish populations respond to nitrate concentrations, given other known factors (e.g. Phosphorus load)	-That rivers are not substitutable
Dose-response		
How apply spatially?	-Challenge is upscaling to all UK -Relevant spatial scale for modelling	
Potential sources of new information		-Welsh Water, Rivers Trust for value of biodiversity, or cost of mitigation measures

Appreciation of biodiversity (aquatic)– Sulphur

Appreciation of biodiversity (aquatic) - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Acidification of rivers and lakes** Increasing S deposition contributes to acidification of rivers and lakes and leads to reduced abundance and diversity of aquatic life in rivers and lakes.	**Reduced appreciation of aquatic biodiversity** Reduced fish abundance leads to reduction in biodiversity value.
Measure of Impact	Change in ANC or pH of freshwaters Change in abundance and diversity of fish and/or other organisms	Change in WTP to maintain biodiversity Change in value of rivers
Data sources	Water quality -EA monitoring data -AWMN monitoring data -Outputs from dynamic models -Known thresholds for ANC for salmonids Fish abundance/diversity (as proxy for wider aquatic biodiversity) -EA data -invertebrate abundance indices (e.g. RIVPACS)	-WTP to maintain abundance of fish or aquatic species ? (Christie et al. 2010) -Other studies are available on aquatic biodiversity
Methodology	-Model atmospheric S contribution to pH or ANC concentrations in freshwater using FAB model. -Model changes in fish population to pH, ANC concentrations. Or: -Model changes in fish populations directly to S deposition	-Link WTP to abundance/diversity of aquatic organisms
Assumptions	-We can separate out atmospheric contribution to acidity in waters.	-That rivers are not substitutable
Dose-response		
How apply spatially?	-Upscaling to all acid-sensitive freshwaters -Relevant spatial scale for modelling	
Potential sources of new information		-Welsh Water, Rivers Trust for value of biodiversity, or cost of mitigation measures

Appreciation of biodiversity (terrestrial)– Nitrogen

Appreciation of biodiversity (terrestrial). - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Eutrophication of terrestrial habitats** Increasing N deposition leads to reduced species richness.	**Reduced appreciation of terrestrial biodiversity** Reduced species richness leads to reduction in biodiversity value.
Measure of Impact	Change in critical load exceedance Change in plant species richness	Change in WTP to maintain biodiversity
Data sources	N Critical load exceedance (1x1km) Habitat occurrence (CEH Landcover) Species occurrence from BRC records ?Modelled UK species richness	-WTP to increase abundance of (non-charismatic) species by 20%, or avoid decline of 55% (Christie et al. 2010)
Methodology	-Calculate proportion of critical load exceedance per habitat OR -Calculate change in species richness per habitat/grid square	-Link WTP to critical load exceedance or to changes in species richness
Assumptions	-Current species richness is in equilibrium with deposition -There are no lags in recovery and/or further damage with changing deposition -Critical Load exceedance is a proxy for current damage (actually is a measure of risk)	-

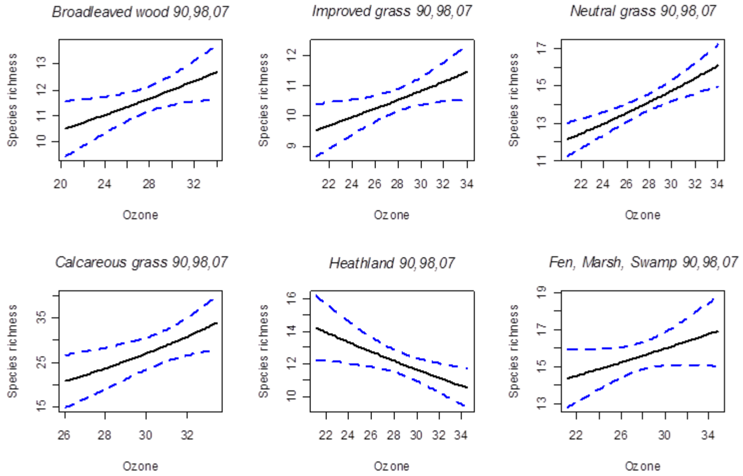
Appreciation of biodiversity (terrestrial). - **Nitrogen**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Dose-response	Relative species richness curves for different habitats (acid grasslands, sand dune grasslands, heaths, bogs) 	
How apply spatially?	-Calculate relative exceedance/change in spp richness for each grid cell ...	Disaggregate total UK value for each habitat to habitat locations
Potential sources of new information	Modelled species richness in each grid cell in UK (CEH data)	

Appreciation of biodiversity (terrestrial)– Sulphur

Appreciation of biodiversity (terrestrial). - **Sulphur**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Acidification of terrestrial habitats** Increasing S deposition leads to reduced species richness.	**Reduced appreciation of terrestrial biodiversity** Reduced species richness leads to reduction in biodiversity value.
Measure of Impact	-Critical load exceedance -Plant species richness	WTP to maintain biodiversity
Data sources	S Critical load exceedance (1x1km) Habitat occurrence (CEH Landcover) Species occurrence from BRC records	-WTP to increase abundance of (non-charismatic) species by 20%, or avoid decline of 55% (Christie et al. 2010)
Methodology	-Calculate proportion of critical load exceedance per habitat N.B. No clear evidence in the literature that acidification has caused species loss in terrestrial habitats.	-Link WTP to critical load exceedance/changes in species richness
Assumptions		
Dose-response		
How apply spatially?		
Potential sources of new information		

Appreciation of biodiversity (terrestrial)– Ozone

Appreciation of biodiversity (terrestrial). - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
Impact/Response	**Ozone toxicity impacts on terrestrial habitats** Increasing ozone concentrations lead to reduced species richness.	**Reduced appreciation of terrestrial biodiversity** Reduced species richness leads to reduction in biodiversity value.
Measure of Impact	Plant species richness	WTP to maintain biodiversity
Data sources	Habitat occurrence (CEH Landcover) Species occurrence from BRC records Countryside Survey data	-WTP to increase abundance of (non-charismatic) species by 20%, or avoid decline of 55% (Christie et al. 2010)
Methodology	-In principle, link ozone to changed species richness. However, we need to understand the observed relationships so far, e.g. whether change in proportion of graminoids, or undesirable species is driving observed counter-intuitive relationships	-Link WTP to ozone induced changes in species richness
Assumptions	-	-
Dose-response	1) Relationships derived from spatial gradient approaches using CS data and ozone.	

<table>
<tr><th>Appreciation of biodiversity (terrestrial).
- Ozone</th><th>Ecosystem Response</th><th>Ecosystem Service, and Valuation</th></tr>
<tr><td></td><td>


2) Dose response relationships from experiments.

A large amount of data exists for the responses of individual species e.g. for >80 species in Hayes et al. (2007) with more data published since then. This data has been used to show which individual species (when growing in a competitive environment) are sensitive to ozone (e.g. see figure for pasture species, EUNIS E2.11) . There are several experiments published or conducted under the ozone umbrella contract using mixed species mesocosms, This information can be used to identify communities at potential risk, and these can then be mapped in relation to past/current/future ozone concentration/flux.
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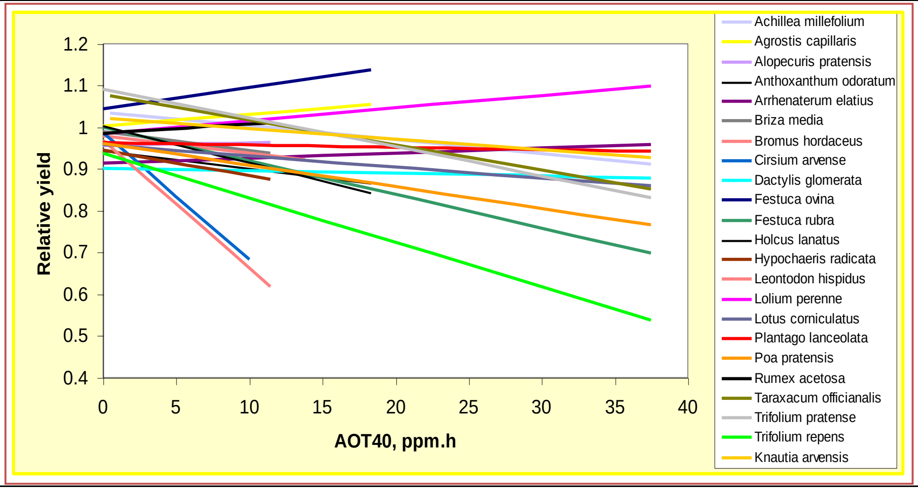
Appreciation of biodiversity (terrestrial). - **Ozone**	**Ecosystem Response**	**Ecosystem Service, and Valuation**
		
How apply spatially?		
Potential sources of new information		

Appendix B. Impact pathway for ozone impacts on wheat production

Ozone damages crop plants by, for example, reducing photosynthesis, causing a yellowing of leaves and premature leaf loss, decreased seed production and reduced root growth, resulting in reduced yield quantity and/or quality and reduced resilience to other stress such as drought. As a consequence, the key components of the food system that ozone interferes with are the productivity of crops, the nutritional value and the stability of food supplies as ozone concentrations and therefore impacts vary from year to year. Some of the UK's most important crops are sensitive (wheat, pulses) or moderately sensitive (maize, potato, sugarbeet) to ozone and effects on the yield of these crops are of national significance (**Table B1**, Mills et al., 2007).

Table B1. The range of sensitivity of agricultural and horticultural crops to ozone (From Mills et al., 2007).

Sensitive	Moderately sensitive	Moderately resistant	Insensitive
Cotton, Lettuce, Pulses, Soybean, Salad Onion, Tomato, Turnip, Watermelon, Wheat	Potato, Rapeseed, Sugarbeet, Tobacco	Broccoli, Grape, Maize, Rice	Barley, Fruit (Plum and Strawberry)

A recent state of knowledge report by the ICP Vegetation (Mills and Harmens, 2011), for the first time, quantified ozone impacts on wheat yield in Europe using the stomatal flux-based methodology. Using the national emissions projections scenario for 2000, ozone pollution in EU27 (+ Norway and Switzerland) was predicted to be causing an average of 13% yield loss for wheat, with an economic loss of €3.2 billion predicted if soil moisture is not limiting. Economic losses per grid square in 2000 were greatest for wheat in the highest producing areas in France, Germany, Belgium, Denmark and the UK, indicating that ozone flux was high enough in these central and northern areas to have an impact on wheat production.

In a UK-focussed study, Mills et al., 2011, quantified ozone effects on crops in on two contrasting ozone years: 2006, representative of a hot, dry and high ozone year that is likely to become more common in the future, and 2008 a typical example of a current year. For three crops, wheat, oilseed rape and potato, economic losses were estimated using a modelling approach that relates the accumulated amount of ozone absorbed by leaves (ozone flux or "phytotoxic ozone dose above a threshold of 6 nmol m^{-2} s^{-1}", POD_6) to effects on seed or tuber yield. This method is the most biologically relevant as it allows for the modifying effects of climate and soil moisture on the phytotoxic ozone dose absorbed by the leaves but currently has only been developed for these three crops. The second method predicted effects based only on the ozone concentration in the air above the leaves and is regarded as being less accurate. Relative to zero ozone flux and using the mean farm gate price for the period 1996 – 2009, the Mills et al., 2011, study showed that ozone pollution impacts on the yield of UK crops in a **typical current year** (e.g. 2008) totalled **£183 million of losses**[1], **representing 6.6% of the total value** for the 8 crops studied. Affected crops[6] include cereals (wheat 5.6% yield loss, barley 3.1% and maize 1%), root crops (sugar beet 2%, potato 0.04%), oilseed rape (7.2%), peas and beans (9.7%) and salad leaf crops (ca. 24%). Under climatic and ozone conditions expected to **occur more frequently in the future** (using 2006 as an example), ozone effects on total yield for the studied crops were slightly higher than those predicted for 2008 at **£205 million**[1] **representing 9.1% of the total value** for the 8 crops studied. Affected crops[1] include cereals (wheat 5.6%, barley 2.7% and maize 3.6%), root crops (sugar beet 8.2%, potato 1.3%), oilseed rape (6.6%), peas and beans (20.9%) and salad leaf crops (24%).

[6] Note: Flux-based values were used for wheat, potato and oilseed rape, AOT40-based values were used for maize, barley, sugar beet, peas and beans, and a value based on the cost of damaging ozone episodes was used for salad leaf crops; Effects on pasture have not been quantified; Salad crop totals for 2006 were used as a surrogate for 2008 totals.

For this study we selected wheat for analysis of effects on marginal costs because wheat is the most important UK crop, it is sensitive to ozone, and the Mills et al., 2011 study indicated that annual losses (relative to zero flux) could be as high as £80 – 90 million. We have also used the flux-based method to fit with LRTAP convention recommendations that this metric should be used for economic impact assessment because of the greater biological relevance and better representation of effects.

The deterministic calculations of ozone impacts on wheat production are shown in **Table B2**. The final estimates of value after uncertainty analysis are shown in Section 3.6.6 in the main report.

Table B2. Net value of ozone on wheat production. Results from deterministic calculations, rounded to nearest £1000.

	Future to 2020 (based on UEP43 scenario) - Reference year 2007
Net Present Value of Benefits (2007 to 2020, £)	-£191,265,000
Equivalent Annual Net Benefit (£)	**-£18,565,000**

The damage cost per unit ozone flux of POD_6wheat (in mmol m^{-2}) calculated deterministically is -£100.4 million EAV for the future scenario (Table B3).

Table B3. Damage cost per unit ozone flux POD_6wheat, rounded to nearest £1000.

Damage cost, per unit ozone flux (POD6 wheat)
-£100,427,000

Appendix C. Impact pathway for nitrogen impacts on biodiversity

Nitrogen impacts on species richness

Nitrogen affects species richness in a wide range of UK habitats. These include acid grasslands (Stevens et al., 2004; Duprè et al., 2010), sand dune grasslands (Jones et al., 2004), mixed grassland, heath and bog, and deciduous woodland (Maskell et al., 2009). In other habitats, loss of plant species diversity due to N has not been observed: calcareous grasslands (van den Berg et al., 2010), woodland epiphytes (Mitchell et al., 2005), Racomitrium heath (Armitage et al., 2012) and Scottish montane habitats (RoTAP 2012). However, in some of these, other changes have occurred which damage their conservation status, such as shifts in species composition, rather than species loss. This direct reduction in biodiversity in some habitats is likely to have adverse impacts on cultural services associated with appreciation of the natural environment.

Dose response relationships

Data from targeted gradient surveys of four UK habitats (Caporn et al. 2012) were re-analysed to derive dose-response relationships for nitrogen on species richness. The four habitats were heaths (including upland and lowland heaths), acid grassland, sand dune grassland and bogs. Each habitat was characterised by over 20 sites, selected along N deposition gradients, controlling as far as possible for confounding gradients of temperature and rainfall. Total species richness of all vascular and lower plants at each site was summed over 5 quadrats, each of 2x2m. Site data for upland and lowland heaths were not significantly different and were therefore combined before deriving equations. Dose response relationships were calculated by curve fitting in Sigmaplot v13.1. Log relationships provided the most parsimonius fit for all habitats except Bogs, where a linear fit was the most appropriate. A quadratic relationship for acid grasslands gave a higher R^2, but was rejected due to the shape of the curve at high N deposition which predicted an increased species richness above 35 kg N ha^{-1} yr^{-1}. All curves were significant. Habitat information and the equations for each habitat are summarised in Table C1.

Table C1. Habitats with targeted N gradient surveys, from Caporn et al. (2012). Heath data from upland and lowland surveys were combined prior to analysis. Species richness was calculated as number of species in an area of 20 m^2 (five random quadrats of 2x2m).

Habitat	Number of sites surveyed	N deposition range (kg N ha^{-1} yr^{-1})	Form of equation	Coefficients (SE)	R^2, SE, (Significance) of equation
Heaths: Upland + Lowland	25 + 27	5.9 – 32.4	f = y0 + a*ln(x)	y0 = 49.6654 (6.5632) a = -11.3114 (2.2716)	0.3315, 6.6414, (p<0.001)
Acid grassland	22	7.8 – 40.8	f = y0 + a*ln(x)	y0 = 65.1623 (7.927) a = -14.026 (2.7211)	0.5705, 6.1451, (p<0.001)
Dune grassland	24	5.4 – 16.8	f = y0 + a*ln(x)	y0 = 98.351 (15.06) a = -20.4662 (6.1534)	0.3346,10.2808, (p=0.003)
Bogs	29	5.9 – 30.9	f = y0 + a*x	y0 = 27.6647 (1.9195) a = -0.2909 (0.1074)	0.2136, 3.6072, (p=0.012)

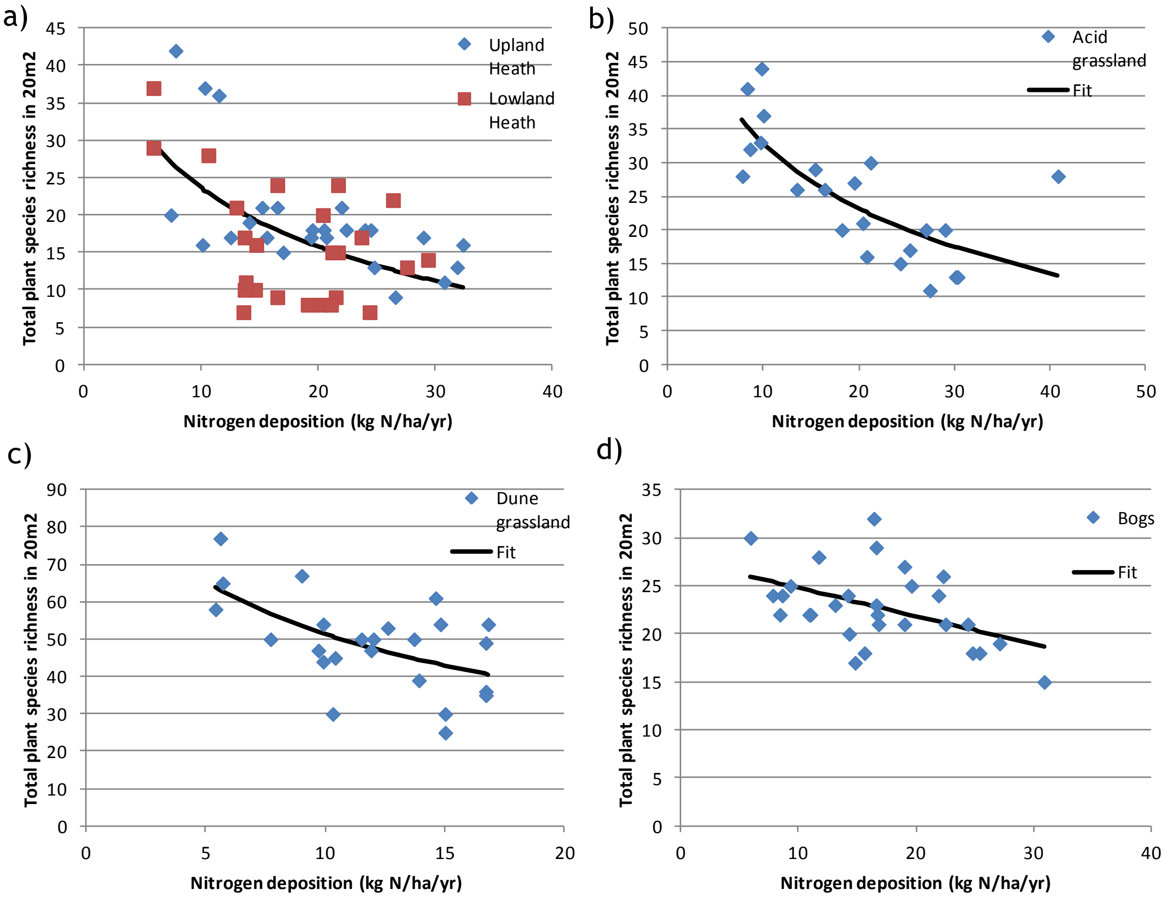


Figure C1. Dose response curves for a) heathland, b) acid grassland, c) dune grassland and d) bogs.

<u>Spatial quantification of N impact on species richness</u>

Total nitrogen deposition data was available at 5x5km resolution for the whole UK. In the absence of spatially explicit information on species richness by habitat across the UK, we made the assumption that N deposition is the only driver of species richness. Using the dose response relationships in Table C1, we calculated for each grid cell, what the species richness would be under the N deposition in each year of the analysis. The percentage difference in species richness from the reference year was then calculated.

<u>Comparison of deterministic calculations for non-charismatic species, for GB: Historical and future scenarios.</u>

In the historical scenario, results show that the benefit to biodiversity for non-charismatic species was highest for acid grassland with an EAV of £8.0m due to its large land area within Great Britain, and also high for heaths with an EAV of £5.3m. Although dune grassland and bogs had comparable WTP values per hectare with the other habitats, their low area across Great Britain meant the total benefit in these habitats was lower. The combined benefit for these four habitats is £14.9m (EAV).

In the future scenario, the benefit for non-charismatic species was highest for heathland, with an EAV of £16.7m, followed by acid grasslands with an EAV of £12.1m, giving a combined benefit for the four habitats of £32.7m (EAV). The WTP values for charismatic species are higher, by roughly a factor of 5, than those for non-charismatic species. Therefore, valuing impacts of nitrogen on charismatic species remains an important knowledge gap, which needs to be addressed.

Table C2. Value of nitrogen on appreciation of biodiversity in the historical and future scenarios, for Great Britain only (i.e. excluding Northern Ireland), showing Equivalent Annual Value, for valuations based on non-charismatic species.

		Non-charismatic species	
		Historical: Reference year 1987, to 2007	**Future: Reference year 2007, to 2020 (based on UEP43 scenario)**
Equivalent Annual Net Benefit (£)	Acid grassland	£8,045,231	£12,146,162
	Heathland	£5,265,505	£16,725,392
	Dune grassland	£109,678	£225,758
	Bogs	£1,464,274	£2,829,380
	Total	**£14,884,688**	**£31,926,692**

Appendix D. Uncertainty analysis on damage costs for ecosystem services

Collated damage costs from Defra air quality valuation reports for historical air pollution scenarios are in **Table D1**. Detailed results of the uncertainty analysis for each habitat type are presented in the following pages. Collated damage costs for future air pollution scenarios are shown in **Table 16**.

Table D1. Collated damage costs (£ per tonne pollutant emitted in UK) plus uncertainty bounds, from Defra air quality valuation reports, **historical** emissions scenarios. Values in black are positive, showing a benefit from decreases in nitrogen dioxide, ammonia or sulphur, values in red are negative, showing a cost due to decreases in nitrogen dioxide, ammonia or sulphur.

	Provisioning Services			*Regulating Services*				*Cultural Services*	
				Net GHG emissions					
	Crop production	**Timber production[4]**	**Livestock production**	CO_2	N_2O	CH_4	**Clean water**	**Recreational fishing**	**Appreciation of biodiversity**
Decreasing Nitrogen dioxide	n.v.	-£2.6 (-£5.1 to -£1.0)[1] (#)	-£5.4 (-£7.1 to -£3.4)[1] (#)	-£30.1 (-£55.3 to -£10.2)[1] #	£6.9 (£3.5 to £10.9)[1] #	n.v.	n.v.	£0.1 (uncertainty not calculated)[1] (#)	£108.1 (£15.6 to £200.1)[1] (#) (not calculated)[3] ##
Decreasing Ammonia	n.v.	-£9.7 (-£18.8 to -£3.8)[1] (#)	-£40.4 (-£52.9 to -£25.6)[1] (#)	-£124.4 (-£228.9 to -£42.2)[1] #	£42.6 (£21.3 to £66.9)[1] #	n.v.	n.v.	£0.3 (uncertainty not calculated)[1] (#)	£823.6 (£122.9 to £1,531.1)[1] (#) (not calculated)[3] ##
Decreasing Sulphur dioxide	n.v.	n.v.	n.v.	n.v.	n.v.	-£0.7 (-£0.2 to -£1.3)[1] #	n.v.	n.v.	n.v.

[1] Defra report NE0117, [2] Defra report AQ0815, [3] Defra report AQ0827
[4] More conservative estimate of the two approaches presented in NE0117.
Robust, # Acceptable, (#) Improvements desirable and not sufficiently robust for policy appraisal at present. n.v. = Not Valued.

Below we present the results from the deterministic calculations and the uncertainty analysis. The output values from the Monte Carlo simulations are presented as a set of summary statistics (mean median, standard deviation, 2.5th and 97.5th percentiles). The distributions of the Monte Carlo simulation outputs are skewed and so the minimum width confidence interval is presented along with the 2.5th and 97.5th percentile (see http://mathapps.net/confidence/confidence.htm).

Histograms of the values of equivalent annual benefit per unit decrease in NHy/NOx emissions for UK (EAV/t) are presented with the mean and minimum width confidence intervals shown by solid and dotted lines respectively. Values reported in the main report are the mean from the deterministic calculations, with the 2.5th and 97.5th percentiles for the 95% confidence intervals.

Results

Acid grass NHy

Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£7,078,483
	Wales	£2,060,073
	Scotland	£7,793,945
	Northern Ireland	£270,065
	UK	£17,202,566
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£687,049
	Wales	£199,954
	Scotland	£756,493
	Northern Ireland	£26,213
	UK	£1,669,708

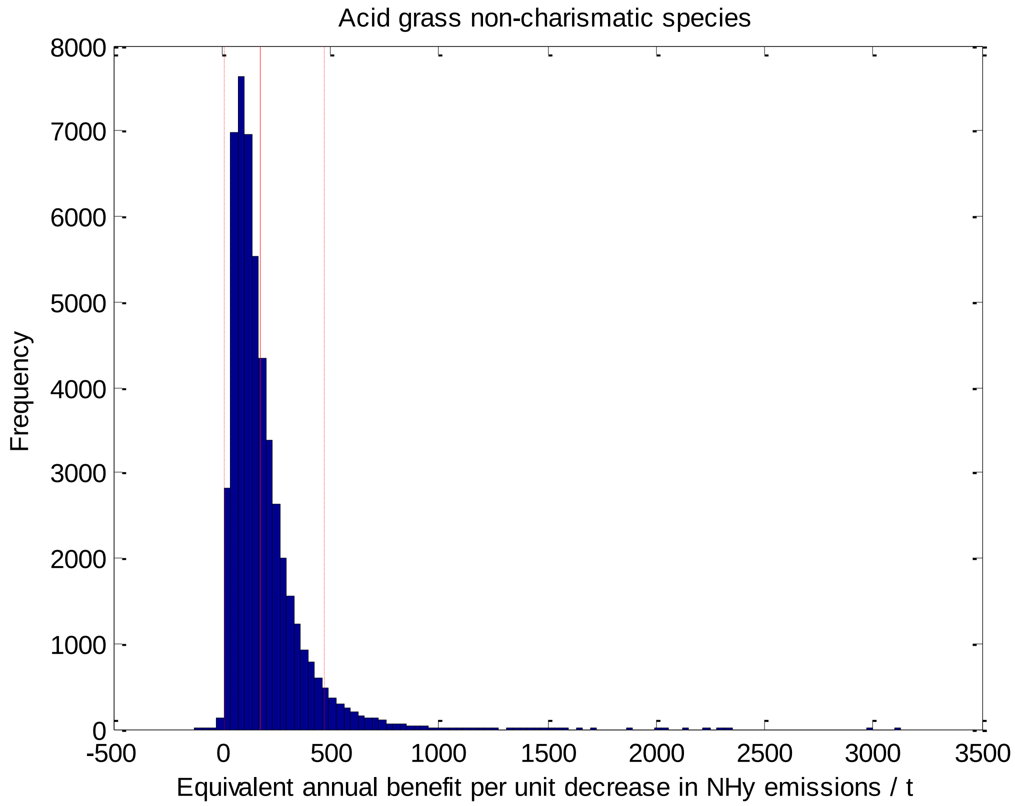
Average change in NHy emissions (as t NH3)	9546
Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)	£174.91

Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£7,317,187	£2,140,005	£7,913,507	£278,029	£17,648,730
Median	£5,608,552	£1,645,432	£6,200,446	£208,240	£13,679,680
Standard deviation	£6,190,472	£1,802,199	£6,314,756	£263,365	£14,546,780
2.5 percentile	£1,015,268	£296,065	£1,312,260	£1,261	£2,647,241
97.5 percentile	£23,493,870	£6,860,532	£24,401,080	£961,487	£55,720,950
Minimum width CI	[£241,063 to £19,200,905]	[£71,853 to £5,635,469]	[£417,918 to £19,913,725]	[-£60,376 to £803,258]	[£904,369 to £45,721,907]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£710,218	£207,712	£768,097	£26,986	£1,713,013
Median	£544,375	£159,708	£601,825	£20,212	£1,327,771
Standard deviation	£600,857	£174,924	£612,920	£25,563	£1,411,934
2.5 percentile	£98,544	£28,737	£127,370	£122	£256,945
97.5 percentile	£2,280,353	£665,894	£2,368,408	£93,323	£5,408,363
Minimum width CI	[£23,398 to £1,863,670]	[£6,974 to £546,988]	[£40,564 to £1,932,857]	[-£5,860 to £77,965]	[£87,779 to £4,437,840]

	Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)
	UK
Mean	£ 181
Median	£ 140
Standard deviation	£ 152
2.5 percentile	£ 27
97.5 percentile	£ 577
Minimum width CI	[£ 7 to £473]



Acid grass non-charismatic species
Frequency
8000
7000
6000
5000
4000
3000
2000
1000
0
-500
0
500
1000
1500
2000
2500
3000
3500
Equivalent annual benefit per unit decrease in NHy emissions / t

Acid grass NOx
Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£23,325,829
	Wales	£17,373,825
	Scotland	£67,506,578
	Northern Ireland	£904,867
	UK	£109,111,099
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£2,264,042
	Wales	£1,686,331
	Scotland	£6,552,295
	Northern Ireland	£87,828
	UK	£10,590,495

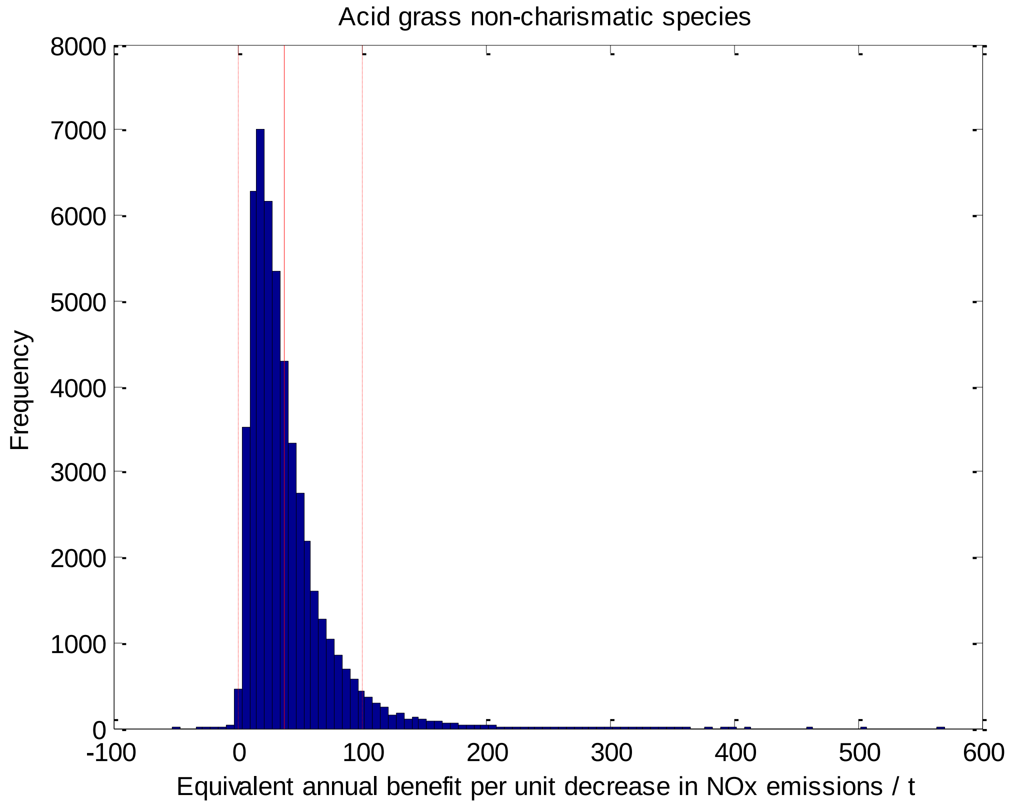
Average change in NOx emissions (as t NO2)	279521
Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)	£37.89

Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£24,229,130	£17,800,670	£67,863,210	£926,171	£110,819,200
Median	£18,605,170	£13,595,430	£53,610,990	£694,435	£86,452,810
Standard deviation	£20,717,610	£15,786,400	£53,624,300	£888,579	£90,759,750
2.5 percentile	£3,184,955	£1,467,528	£11,320,980	-£19,451	£16,336,670
97.5 percentile	£78,703,490	£58,890,560	£207,053,300	£3,258,284	£347,128,000
Minimum width CI	[-£145201 £6410702]	[-£824569, £49575778]	[£3443559, £171364687]	[-£179908, £2757226]	[£2787396, £286757061]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£2,351,717	£1,727,761	£6,586,910	£89,896	£10,756,280
Median	£1,805,848	£1,319,594	£5,203,568	£67,403	£8,391,245
Standard deviation	£2,010,884	£1,532,253	£5,204,859	£86,247	£8,809,284
2.5 percentile	£309,137	£142,441	£1,098,832	-£1,888	£1,585,662
97.5 percentile	£7,639,084	£5,716,011	£20,096,920	£316,254	£33,692,790
Minimum width CI	[-£14093, £6222327]	[-£80034, £4811903]	[£334237, £16632926]	[-£17462, £267621]	[£270549, £27833091]

	Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)
	UK
Mean	£39
Median	£30
Standard deviation	£32
2.5 percentile	£6
97.5 percentile	£121
Minimum width CI	[£1, £100]



Bogs NHy
Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£2,948,870
	Wales	£249,045
	Scotland	£694,499
	Northern Ireland	£507,288
	UK	£4,399,702
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£286,222
	Wales	£24,173
	Scotland	£67,409
	Northern Ireland	£49,238
	UK	£427,042

Average change in NHy emissions (as t NH3)	9546
Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)	£44.73

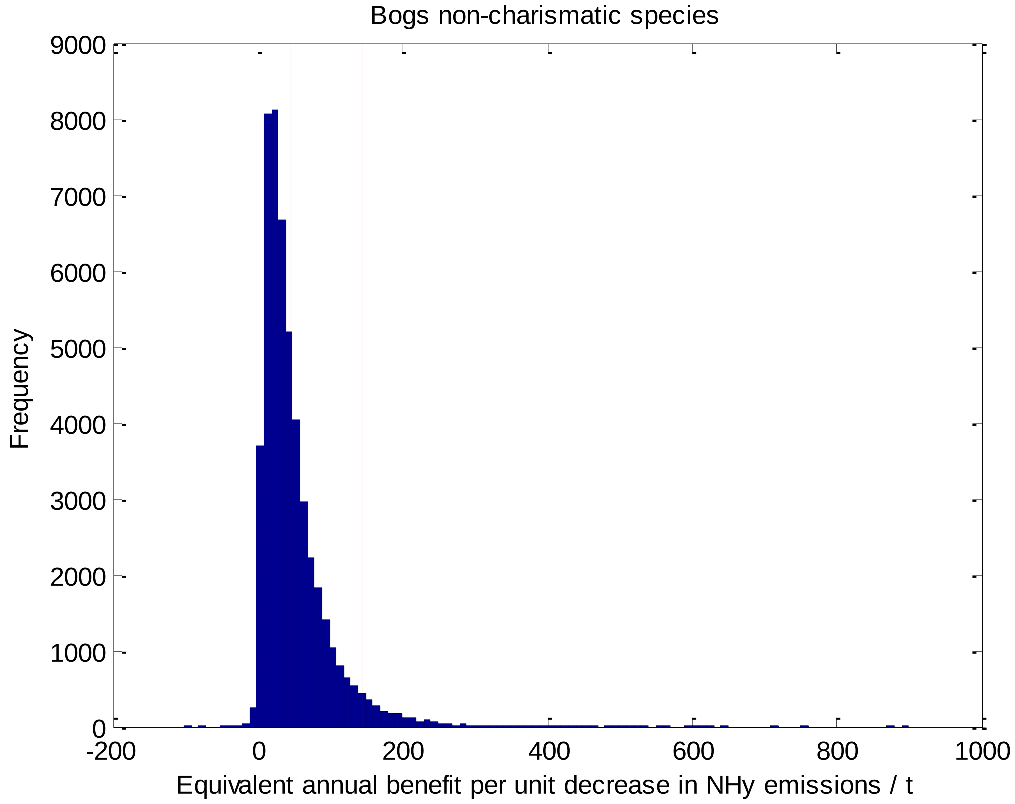
Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£3,229,624	£271,583	£730,886	£541,804	£4,773,897
Median	£2,357,976	£198,534	£545,683	£376,540	£3,480,007
Standard deviation	£3,064,678	£256,270	£654,651	£601,089	£4,551,773
2.5 percentile	£242,720	£23,651	£77,160	-£65,209	£335,448
97.5 percentile	£11,341,510	£955,564	£2,469,031	£2,106,800	£16,808,880
Minimum width CI	[-£173392, £9215495]	[-£16129, £769904]	[0, £2012250]	[-£178960, £1803258]	[-£277402, £13698619]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*

Mean	£313,472	£26,360	£70,941	£52,588	£463,362
Median	£228,869	£19,270	£52,965	£36,548	£337,775
Standard deviation	£297,462	£24,874	£63,541	£58,343	£441,802
2.5 percentile	£23,559	£2,296	£7,489	-£6,329	£32,559
97.5 percentile	£1,100,825	£92,749	£239,648	£204,489	£1,631,497
Minimum width CI	[-£16830, £894470]	[-£1565, £74728]	[0, £195312]	[-£17370, £175027]	[-£26925, £1329610]

	Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)
	UK
Mean	£49
Median	£35
Standard deviation	£47
2.5 percentile	£3
97.5 percentile	£173
Minimum width CI	[-£3, £143]



Bogs NOx

Deterministic calculations

Net Present Value of Benefits (2007 to 2020, £)	England	£9,814,813
	Wales	£1,422,199
	Scotland	£14,020,938
Net Present Value of Benefits (2007 to 2020, £)	Northern Ireland	£1,586,018
	UK	£26,843,968
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£952,641
	Wales	£138,041
	Scotland	£1,360,894
	Northern Ireland	£153,941
	UK	£2,605,518

Equivalent Annual Net Benefit (£)

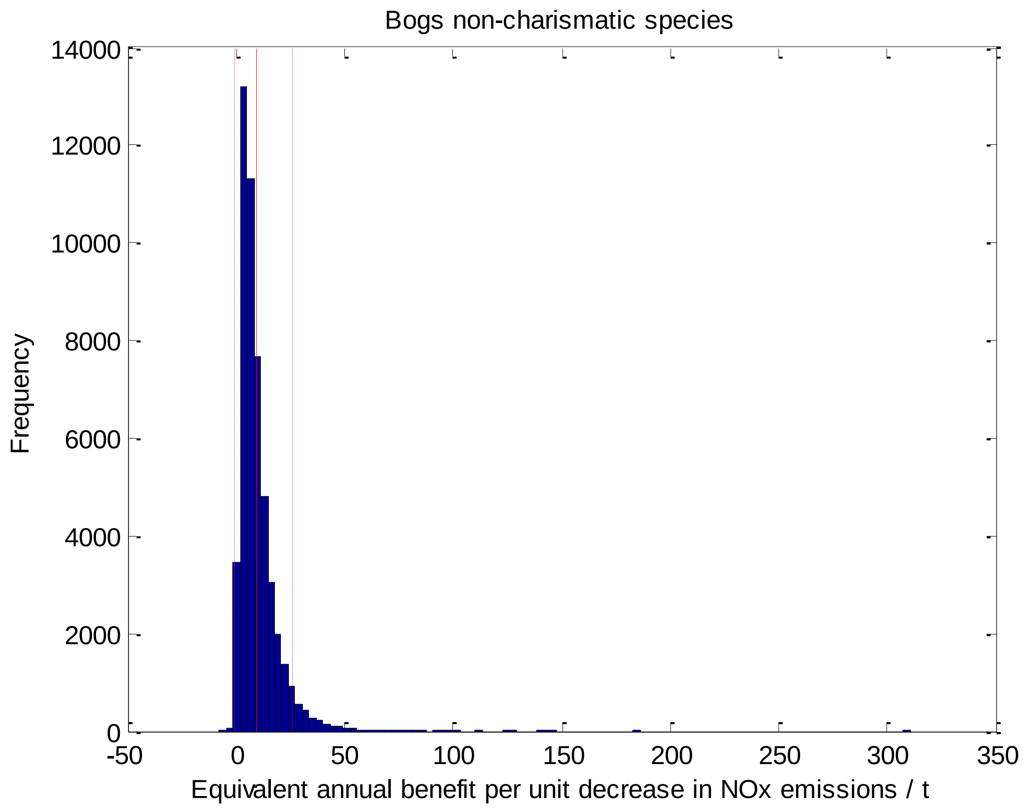
Average change in NOx emissions (as t NO2)	279521
Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)	£9.32

Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£10,501,360	£1,482,141	£14,045,610	£1,625,693	£27,654,810
Median	£7,756,747	£1,084,599	£10,616,360	£1,152,189	£20,607,630
Standard deviation	£9,848,589	£1,431,276	£12,590,860	£1,773,904	£25,536,440
2.5 percentile	£1,059,171	£105,350	£1,463,569	-£143,363	£2,662,887
97.5 percentile	£35,844,460	£5,188,164	£46,688,690	£6,126,557	£93,354,190
Minimum width CI	[-£182776, £29058685]	[-£86622, £4225266]	[-£247371, £38020281]	[-£564101, £5151591]	[-£1187350, £75559479]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£1,019,278	£143,859	£1,363,289	£157,792	£2,684,219
Median	£752,882	£105,273	£1,030,441	£111,833	£2,000,209
Standard deviation	£955,920	£138,922	£1,222,089	£172,178	£2,478,607
2.5 percentile	£102,805	£10,225	£142,056	-£13,915	£258,464
97.5 percentile	£3,479,120	£503,571	£4,531,678	£594,653	£9,061,105
Minimum width CI	[-£17741, £2820482]	[-£8408, £410111]	[-£24010, £3690308]	[-£54753, £500021]	[-£115246, £7333922]

	Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)
Mean	£10
Median	£7
Standard deviation	£9
2.5 percentile	£1
97.5 percentile	£33
Minimum width CI	[-£1, £26]



Dune grass NHy

Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	-£23,869
	Wales	-£48,033
	Scotland	£11,650
	Northern Ireland	£13,268
	UK	-£46,984
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	-£2,317
	Wales	-£4,662
	Scotland	£1,131
	Northern Ireland	£1,288
	UK	-£4,560

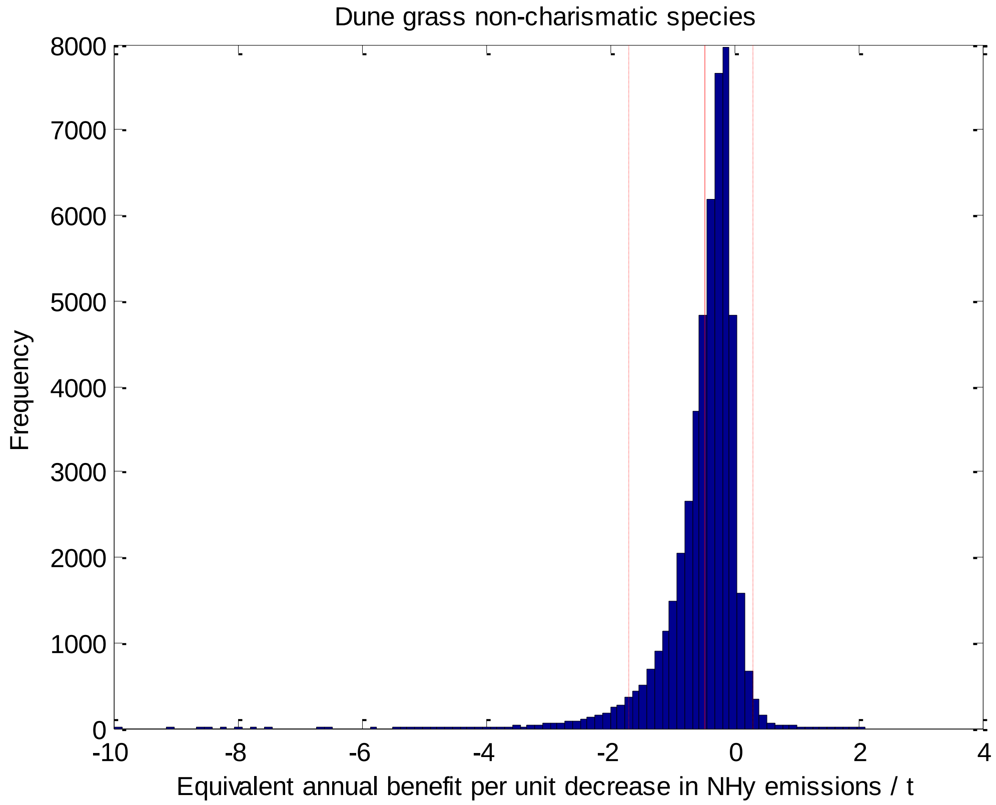
Average change in NHy emissions (as t NH3)	9546
Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)	-£0.48

Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	-£23,423	-£48,806	£12,796	£13,487	-£45,945
Median	-£17,732	-£33,831	£9,173	£9,478	-£32,538
Standard deviation	£20,870	£59,137	£12,700	£14,560	£54,435
2.5 percentile	-£78,057	-£201,444	£1,128	-£806	-£185,732
97.5 percentile	-£2,666	£18,829	£46,293	£52,028	£18,235
Minimum width CI	-£23,423	-£48,806	£12,796	£13,487	-£45,945

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	-£2,273	-£4,737	£1,242	£1,309	-£4,460
Median	-£1,721	-£3,284	£890	£920	-£3,158
Standard deviation	£2,026	£5,740	£1,233	£1,413	£5,284
2.5 percentile	-£7,576	-£19,552	£109	-£78	-£18,027
97.5 percentile	-£259	£1,828	£4,493	£5,050	£1,770
Minimum width CI	-£2,273	-£4,737	£1,242	£1,309	-£4,460

	Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)
	UK
Mean	-£0.47
Median	-£0.33
Standard deviation	£0.56
2.5 percentile	-£1.93
97.5 percentile	£0.19
Minimum width CI	[-£1.69, £0.31]



Dune grass NOx
Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£986,523
	Wales	£316,069
	Scotland	£1,083,584
	Northern Ireland	£66,924
	UK	£2,453,099
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£95,753
	Wales	£30,678
	Scotland	£105,174
	Northern Ireland	£6,496
	UK	£238,102

Average change in NOx emissions (as t NO2)	279521
Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)	£0.85

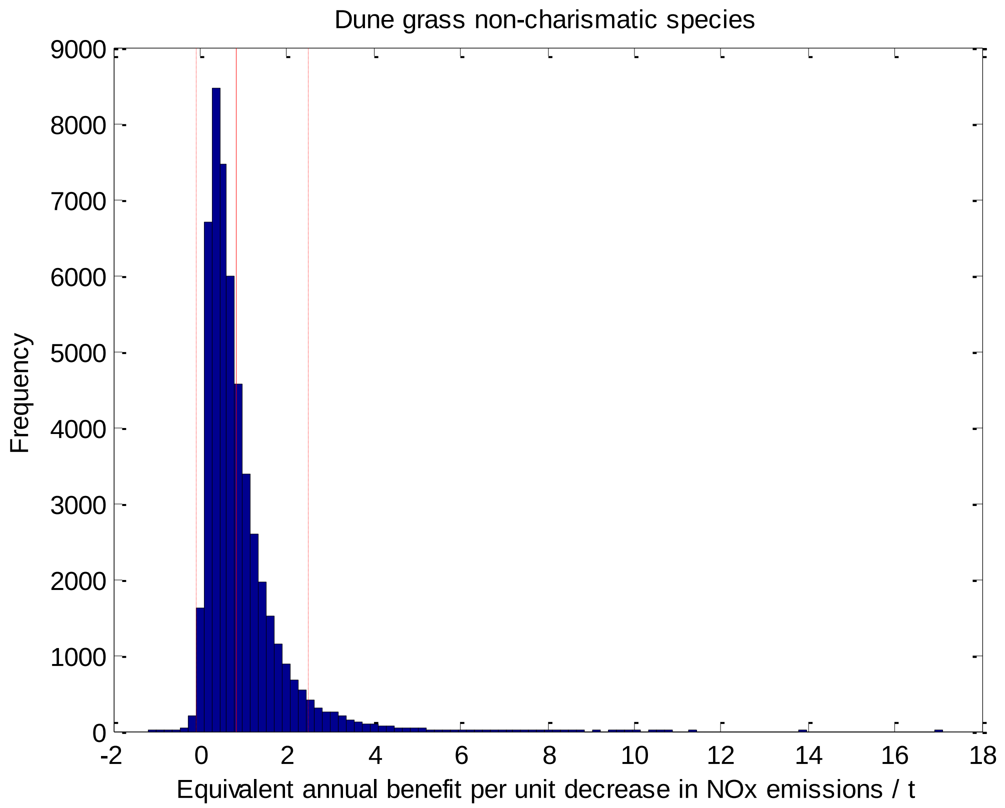
Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£1,004,213	£319,292	£1,078,855	£68,832	£2,471,193
Median	£735,856	£227,912	£815,126	£48,828	£1,829,689
Standard deviation	£964,062	£342,933	£959,478	£72,327	£2,331,372
2.5 percentile	£50,875	-£44,475	£102,372	-£2,938	£129,088
97.5 percentile	£3,546,354	£1,216,327	£3,601,550	£259,957	£8,612,901
Minimum width CI	[-£98864, £2902726]	[-£123277, £1015841]	[-£29852, £2967180]	[-£17852, £214376]	[-£159793, £7177581]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£97,471	£30,991	£104,715	£6,681	£239,858
Median	£71,423	£22,121	£79,117	£4,739	£177,593

Standard deviation	£93,573	£33,286	£93,128	£7,020	£226,287
2.5 percentile	£4,938	-£4,317	£9,936	-£285	£12,530
97.5 percentile	£344,215	£118,059	£349,572	£25,232	£835,982
Minimum width CI	[-9596, 281743]	[-£11965, £98599]	[-£2897, £287999]	[-£1733, £20808]	[-£15510, £696667]

	Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)
	UK
Mean	£0.86
Median	£0.64
Standard deviation	£0.82
2.5 percentile	£0.05
97.5 percentile	£3.04
Minimum width CI	[-£0.07, £2.51]



Heathlands NHy
Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£8,935,243
	Wales	£1,080,297
	Scotland	£8,062,607
	Northern Ireland	£1,059,435
	UK	£19,137,583
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£867,269
	Wales	£104,855
	Scotland	£782,569
	Northern Ireland	£102,830
	UK	£1,857,524

Average change in NHy emissions (as t NH3)	9546
Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)	£194.58

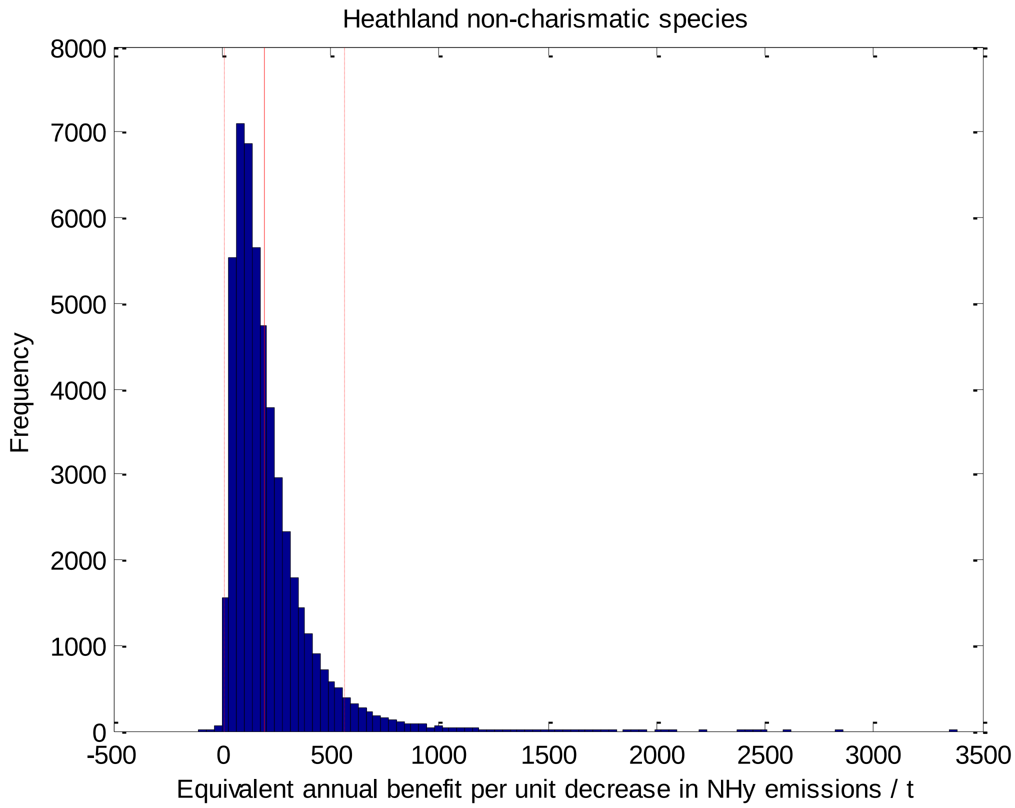
Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£10,070,790	£1,191,614	£8,294,172	£1,151,680	£20,708,250
Median	£7,596,033	£904,614	£6,550,322	£833,147	£15,897,450
Standard deviation	£8,885,137	£1,040,846	£6,573,441	£1,224,895	£17,602,710
2.5 percentile	£1,356,879	£167,714	£1,467,836	-£156,184	£3,023,449
97.5 percentile	£33,688,900	£3,957,537	£25,688,880	£4,379,998	£67,719,240
Minimum width CI	[£368290, £27179101]	[£32273, £3176138]	[£506387, £20845380]	[-£436518, £3684079]	[£582701, £54424245]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£977,487	£115,660	£805,045	£111,784	£2,009,976
Median	£737,283	£87,803	£635,785	£80,867	£1,543,031

Standard deviation	£862,405	£101,026	£638,029	£118,890	£1,708,547
2.5 percentile	£131,701	£16,279	£142,471	-£15,159	£293,461
97.5 percentile	£3,269,898	£384,125	£2,493,403	£425,130	£6,572,936
Minimum width CI	[£35747, £2638046]	[£3132, £308281]	[£49151, £2023285]	[-£42369, £357582]	[£56558, £5282503]

	Equiv Annual Benefit per unit DECREASE in NHy emissions for UK (EAV/t)
	UK
Mean	£213
Median	£163
Standard deviation	£183
2.5 percentile	£31
97.5 percentile	£697
Minimum width CI	[£6.88, £561.437]



Heathlands NOx
Deterministic calculations

		Future: Reference year 2007, to 2020 (based on UEP43 scenario)
Net Present Value of Benefits (2007 to 2020, £)	England	£32,870,879
	Wales	£8,514,710
	Scotland	£112,853,605
	Northern Ireland	£3,311,516
	UK	£157,550,710
	Annuity	10.3
Equivalent Annual Net Benefit (£)	England	£3,190,499
	Wales	£826,451
	Scotland	£10,953,748
	Northern Ireland	£321,421
	UK	£15,292,120

Average change in NOx emissions (as t NO2)	279521
Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)	£54.71

Uncertainty calculations

	Net Present Value of Benefits (2007 to 2020, £)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£35,478,970	£8,902,435	£113,394,200	£3,485,762	£161,261,400
Median	£26,709,550	£6,700,026	£89,141,660	£2,536,562	£125,397,100
Standard deviation	£31,630,680	£8,077,488	£90,603,800	£3,695,619	£133,273,200
2.5 percentile	£4,468,383	£766,128	£19,091,240	-£478,287	£24,456,470
97.5 percentile	£119,397,400	£30,148,150	£351,009,300	£13,059,230	£510,718,500
Minimum width CI	[£199,524, £96,153,021]	[-£300,382, £24,949,313]	[£4,436,344, £284,859,639]	[-£1,281,457, £11,040,370]	[£3,493,968, £415,392,295]

	Equivalent Annual Net Benefit (£)				
	England	*Wales*	*Scotland*	*Northern Ireland*	*UK*
Mean	£3,443,645	£864,084	£11,006,220	£338,334	£15,652,280
Median	£2,592,471	£650,315	£8,652,230	£246,203	£12,171,240

Standard deviation	£3,070,124	£784,014	£8,794,148	£358,703	£12,935,710
2.5 percentile	£433,708	£74,362	£1,853,026	-£46,423	£2,373,783
97.5 percentile	£11,588,890	£2,926,227	£34,069,520	£1,267,549	£49,571,140
Minimum width CI	[£19,366, £9,332,763]	[-£29,156, £2,421,620]	[£430,599, £27,648,925]	[-£124,380, £1,071,596]	[£339,130, £40,318,629]

	Equiv Annual Benefit per unit DECREASE in NOx emissions for UK (EAV/t)
	UK
Mean	£56.15
Median	£43.58
Standard deviation	£46.50
2.5 percentile	£8.50
97.5 percentile	£178.38
Minimum width CI	[£2.36, £146.20]