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The impacts of ozone on nature conservation: a review and recommendations for research and policy

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Executive Summary

- Ozone is globally the most important gaseous pollutant causing effects on vegetation.
- While a number of reviews have evaluated the evidence of impacts of ozone on semi-natural ecosystems, none of these has specifically focussed on the priorities of nature conservation agencies.
- For this reason, the extent to which ozone represents a significant threat to achieving national Biodiversity Action Plan (BAP) targets for Priority Species and Priority Habitats in the UK is unclear. This report provides an initial assessment of the risk from ozone to BAP habitats, focussing on vascular plants.
- It was not possible to assess the sensitivity of BAP Priority Species, as no studies of the effects of ozone have been conducted on these species.
- The sensitivity of BAP Priority Habitats was assessed, drawing on information from major reviews, relevant experimental studies in the UK, and data syntheses defining the relative sensitivity of species and communities.
- For woodlands, the major focus of ozone research has been on trees. Beech and birch are sensitive to ozone, while oak and Scots pine have also shown adverse effects at concentrations found in the UK.
- The direct and indirect effects of ozone on woodland ground flora are poorly understood, although there is evidence that these communities may be sensitive to ozone.
- Grasslands are the best studied habitats in terms of ozone sensitivity with several common positive indicator species reported to be ozone sensitive.
- Studies of ozone effects on grassland communities have reported changes in community composition at concentrations found in the UK. In one study, these effects of ozone led to a change in composition which was unfavourable from a conservation perspective.
- Other habitats, such as wetlands, heaths, montane and inland rock habitats are poorly studied although there is some evidence that montane habitats and bogs are sensitive to ozone.
- An assessment of the exposure to ozone of BAP Priority Habitats was carried out by comparing their national distributions with mean six-month AOT40 values.
- All but one BAP Priority Habitat (lowland fens) in England have over 80% of their national distribution in areas that are likely to exceed critical levels of ozone exposure. The highest exposures are of Priority Habitats with a primarily southern distribution.
- In Scotland and Wales, upland habitats have the highest exposure to ozone. In Wales, as in England, most Priority Habitats have the majority of their distribution in areas that are likely to exceed critical levels.
- Very little of the area of Northern Ireland experiences ozone exposures above the critical level although there is a need for improved monitoring in this region.
- There is a growing body of evidence that models of absorbed dose or flux into the leaf provide a more realistic basis for ozone risk assessment. AOT40 exposure was compared to modelled flux for oak and productive grass in four locations.
- Whilst the results are illustrative rather than predictive, there is evidence from the flux models that BAP Priority Habitats in Scotland and Wales are at greater risk of ozone impacts than is indicated by current assessments based on AOT40.

- Analysis of trends at rural sites in the UK suggest that mean ozone concentrations have tended to increase over the last two decades, whilst peak concentrations have tended to decline.
- These trends are likely to continue based on likely emission control policies. It is unlikely that ozone exposures will be any lower in southern and central Britain by 2020, while exposures may increase in more remote areas of northern and western Britain which are more influenced by changes in hemispheric background concentrations.
- Emission control policies in Europe are likely to have a greater effect in reducing AOT40 exposures than in reducing flux, but flux is likely to be a more reliable indicator of effects on sensitive habitats.
- Climate change will be an important modifier of ozone exposure and impacts, and hence assessments of the future effects of ozone need to take this into account.
- Ozone is, and is likely to remain, a significant threat to many BAP Priority Habitats. However, the knowledge base on which to assess these specific risks is extremely small, and a targeted programme of research to address these gaps is urgently needed.
- Evaluation of emission control policies both in the UK and the EU gives priority to benefits for human health. There is a need for conservation agencies to ensure that threats to biodiversity and the delivery of national BAP targets are given adequate weight in these evaluations.

1. Introduction

1.1 Background

Ozone is globally the most important gaseous pollutant causing effects on vegetation (Ashmore, 2005). Ozone is not emitted directly into the atmosphere, but is formed there as a result of a complex series of photochemical reactions from primary emissions of nitrogen oxides (NO_x) and reactive volatile organic compounds (VOCs). The emissions of nitrogen oxides arise primarily from high temperature fuel combustion, e.g. in transport and energy generation, while emissions of VOCs arise from low temperature combustion, e.g. in transport and small boilers, from a range of industrial sources using solvents, from petroleum refining and distribution, and as biogenic emissions, mainly from forests (NEGTAP, 2001).

These reactions leading to ozone formation from anthropogenic sources are favoured by high temperatures and high levels of solar radiation, and hence elevated ozone concentrations are primarily a summer phenomenon. Ozone is essentially the key toxic and phytotoxic component of photochemical (summer) smogs. There is a relatively high natural background concentration (20-40 ppb; Volz and Kley, 1998) of ozone arising from downward transport from the stratosphere and from reactions between NO_x arising from natural sources, such as soils and lightning, and biogenic VOCs.

Ozone uptake by plants is almost entirely through the stomata into the sub-stomatal cavity, where it results in the oxidation of sensitive components of the plasmalemma and, subsequently, cytosol. The inability to repair or compensate for altered membrane permeability can manifest itself as visible injury, for example bleaching, bronzing and chlorosis in broad-leafed plants and tip necrosis in conifers. Symptoms of acute injury are generally associated with short-term high exposure to ozone. Chronic exposure does not always result in visible injury, but reductions in plant growth are well documented and long-term ozone exposure can result in shifts in species composition in semi-natural communities (Furher *et al*., 1997). In some species, it is also possible for chronic ozone exposure to cause plants to favour shoot over root growth, leading to a decreased root-shoot ratio and a relative increase in above-ground biomass (Mooney and Winner, 1991). This effect appears to be caused by the impairment of assimilate translocation from leaves to roots (Rennenberg *et al*., 1996).

At rural sites in the UK, a diurnal cycle in ozone concentration is observed, typically peaking in the mid-afternoon and reaching a minimum during the night; this cycle can have a large amplitude of 10 ppb (1990-1996 average) in lowland areas (Coyle *et al*., 2002). Vegetation can be exposed to peaks in ozone concentration well over the mean background concentration, resulting in a greater occurrence of acute damage symptoms. To account for this variation, experimental studies have exposed plants to differing background and peak ozone concentrations.

The cumulative damage caused by ozone to vegetation is commonly assessed using the AOT40 index. This index, which was developed for risk assessment of ozone effects on vegetation, calculates the accumulative sum of all hourly ozone concentrations above a threshold of 40ppb over a growing season (Fuhrer *et al*., 1997). Critical levels, above which significant effects on sensitive plant species may occur, have been defined using the AOT40 index (CLRTAP, 2006). This assessment focussed on the critical levels for perennial dominated semi-natural ecosystems and forests, for which the AOT40 is calculated over a growing period of 6 months. According to current estimates (e.g. Coyle *et al*., 2002), large areas of Britain are exposed to AOT40 values in excess of critical levels with particularly high values in south-east England as a result of high NO_x and VOC emissions and a warmer climate. High AOT40 values are also found in upland areas. Unlike lowland areas, which tend to experience ozone depletion at night, upland sites have a relatively small diurnal variation in ozone concentration (1990-1996 average of 2.6 ppb at the most elevated sites; Coyle *et al*., 2002). This is caused by higher levels of night-time atmospheric turbulence leading to entrainment of ozone from the free troposphere and, subsequently, greater exposure of vegetation to ozone over a 24 hour period.

The importance of ozone effects on vegetation was first recognised in the form of visible injury to crop species in the Los Angeles basin in the 1950s. Since that time, effects of ozone in causing a range of effects on crops and forests have been reported in every continent, and the impacts of ozone have become of global concern (Emberson *et al*., 2003). However, most studies of the effects of ozone have focussed on agricultural crops and commercial forestry. In contrast, a much smaller number of studies have considered the impacts of ozone on biodiversity, or on the composition and function of major semi-natural plant communities.

There is considerable uncertainty in quantifying the impact of ozone on semi-natural communities. Unlike the relatively homogeneous canopies of agricultural crops, a wide-range of species with differing sensitivities to ozone occur in these communities and studies on individual plants grown in isolation may not be indicative of impacts that occur *in situ*. Additionally, in semi-natural communities commonly used indicators of ozone damage, such as productivity or visible damage may be less important than shifts in species composition, loss of biodiversity or reduced seed production.

A number of reviews have evaluated the evidence of impacts of ozone on semi-natural vegetation (e.g. Davison and Barnes, 1998; Bassin *et al*., 2007). These reviews provide a valuable synthesis and interpretation of the effects of ozone that have been observed in experimental studies on individual plants, simple artificial communities composing a small number of species, and on real plant communities. These experiments have involved manipulating ozone concentrations in experimental chambers in either controlled environmental conditions or in the field. A small number of studies have released ozone in the field or assessed spatial or temporal correlations of plant responses with ozone concentrations. Experimental studies are typically 3 weeks to 2 years duration. Very few studies have been conducted for 3 years or more, although there is evidence that the effects of ozone on species composition are gradual and cumulative (Volk *et al*., 2006).

However, none of these academic reviews is specifically focussed on the priorities of the nature conservation agencies to preserve and enhance the status of threatened species and habitats. In the UK, policy on nature conservation is strongly focussed on commitments under the Habitats Directive, the UK Biodiversity Action Plan (BAP) and national targets for the condition of SSSIs/ASSIs. This report focuses on BAP Priority Habitats but these also encompass most Annex I habitats (under the Habitats Directive) as well as SSSI/ASSI habitat features (the relationship between the different habitat classifications is detailed in the NBN Habitats Dictionary (http://www.nbn.org.uk/habitats/)). The UK BAP identifies Priority Species and Priority Habitats in terms of national conservation objectives, and, for each of these, aims to develop mechanisms to assess their current status, identify major threats and develop policies both to enhance the status of existing sites and to increase the national extent of the Priority Habitats and the populations of Priority Species.

However, the extent to which air pollution, and ozone specifically, represents a significant threat to achieving national targets for Priority Species and Priority Habitats is unclear. It is important to note that species (and ecotypes within species) vary in their sensitivity to ozone, and that, at least in terms of above-ground biomass, ozone can cause increases, as well as decreases. Hence, by altering the competitive balance between plant species, ozone can cause changes in species composition which could either favour or work against key management objectives, and against indicators of favourable status for a particular site. A key element of this report is therefore an assessment of whether the effects of ozone are likely to decrease, or increase, the likelihood of achieving key BAP objectives for Priority Habitats.

1.2 Objectives and structure of the report

The aim of this report is to provide a first national assessment of ozone risks to Priority Habitats and Priority Species of vascular plants using currently available data. The specific objectives are:-

- To summarise the results of recent studies of the impacts of ozone on nature conservation (in this case BAP Priority Habitats).
- To undertake a systematic risk assessment to identify BAP habitats at greatest risk of impacts of ozone and to assess how this risk might change in the future.
- To identify cases in which ozone may adversely affect the achievement of favourable status.
- To identify key gaps in knowledge, and priorities in terms of conservation objectives.
- To assess how policy initiatives might mitigate the possible impacts of ozone on habitats of conservation value in the UK over the next 20-30 years.

We emphasise very strongly that this report represents an initial assessment of the impacts of ozone in relation to nature conservation in the UK, and the implications for conservation management and emission control policy. Within the scope of this exercise, it has not been possible to conduct a comprehensive and detailed evaluation of all aspects of ozone impacts on species and habitats of concern, or of all possible policy interventions to reduce these impacts. Partly, this is because of the limited scope of this exercise, but primarily it is because information on the effects of ozone on key species and habitats is lacking or very limited. A key aim of the report, by developing an initial evaluation of species and habitat sensitivity linked to a preliminary assessment of the ozone exposure of key habitats, is to identify major gaps in knowledge and to suggest priorities for future work by the conservation agencies.

1.3. Methodology

1.3.1 Report Structure and Information Sources

Given the limited scope of this exercise, it was not possible to conduct a detailed review and assessment of all the information published in peer-reviewed papers and in reports. The structure of the report, and the information used for the three major components of the assessment, is summarised below.

Section 2 reviews the evidence available on the impacts of ozone on UK plant species and communities. For the assessment of sensitivity of BAP Priority Habitats, we have relied on the following key sources:-

- Major reviews and individual studies of particular relevance to the habitat of concern, including evidence of impacts in the UK.
- Experimental studies conducted under the Defra-funded 'Ozone Umbrella' (http://www.airquality.co.uk/archive/reports/cat10/0406021456_O3_Umbrella_2001_finalreport.pdf) contracts. These contracts have supported a range of studies, with a particular focus on upland communities. The information used has been drawn from final contract reports in 2001 and 2006, and ongoing work under the current contract.
- Syntheses of experimental studies aimed at defining the relative sensitivity of different species and communities, drawing on two assessments conducted by the Centre for Ecology and Hydrology, Bangor. The first, the OZOVEG database, provides an index of sensitivity for 83 vascular plant species (Hayes *et al*., 2007), and has also been used to assess the sensitivity of major vegetation types under the EUNIS pan-European habitat classification (Mills *et al*., 2007). The second is a predictive model of community sensitivity, CORI, which has been applied to NVC grassland communities (Jones *et al*., 2007).

The UK BAP also identifies a number of Priority Species. However, no information was found related to ozone effects on any of these species (see Section 2.8). Therefore the analysis has focussed on Priority Habitats.

This information is considered in Section 2 in the context of positive indicator species for the status of that Priority Habitat. This approach allows us to consider not only whether a particular Priority Habitat contains ozone-sensitive species, but also whether ozone is likely to decrease, or even increase, the likelihood of a site of that habitat being in favourable condition. Evidence of community level sensitivity is also considered, using the CORI index for grasslands, and, where possible, direct experimental evidence of the direction of any changes in species composition caused by ozone in artificial or real communities. Having established the sensitivity of key Priority Habitats a second element of the assessment is to evaluate the exposure of each Priority Habitat to ozone. This work, which is described in *Section 3*, primarily focuses on the AOT40 index.

It was not possible to apply phenological data to vary the relevant 6-month growth period across the country. Instead, data on 5 year average values of AOT40 over the country for the period April-September were used. These national maps were based on the period 1999-2003, the latest 5 year period for which data are available. The maps used are based on a modelled spatial interpolation of the national monitoring network data, and were provided by Dr. Mhairi Coyle (CEH Edinburgh). This mapping exercise shows a range of exposures of UK vegetation which range from 2000-10000 ppb.h. This compares with a critical level set for semi-natural ecosystems and forests of 5000 ppb.h. Thus there is clearly a potential for adverse effects of ozone on sensitive ecosystems, since some areas of the UK have ozone exposures that exceed the critical level.

This evaluation was carried out on a country-specific basis using data for England, Wales and Scotland, using information on the distribution of BAP Priority Habitats within each country. Northern Ireland was excluded as BAP distribution maps could not be provided in the timeframe of the project. However, as discussed further in Chapter 3, the limited available data suggest that critical levels of ozone based on AOT40 are not currently exceeded in Northern Ireland.

The AOT40 approach only determines the ozone exposure external to an individual plant or above a plant canopy. However, the primary site of ozone effects is within the leaf, and therefore it would be better to base an assessment of ozone impacts on the absorbed internal dose of ozone. This is analogous to relating effects of air pollutants on human health to the absorbed dose within the body rather than the external concentration. An assessment based on absorbed dose needs to take account of external factors, such as climate and growth stage, which influence the flux of ozone through the stomata to sites of damage within the leaf. For example, stomatal fluxes of ozone in warm, humid conditions with moist soil can be much greater that in hot, dry conditions with dry soil because stomata will be open to a greater extent and for greater time periods. Recently, flux-based critical levels have been set which, like the AOT40 concept, are based on accumulated flux of ozone during a growing season above a critical flux threshold (CLRTAP, 2006).

Application of flux-based risk assessment requires detailed computer models. Furthermore, although these models have been developed and parameterised for monocultures of crops and productive forest species, there are still major problems in developing appropriate models for semi-natural plant communities with a mix of species (Ashmore *et al*., 2007). However, because a flux-based risk assessment might lead to quite different spatial distribution of the risks of ozone impacts, it is important to assess whether use of AOT40 or flux indices give a different picture of the risk of ozone impacts in different parts of the UK. Within the limited scope of this report, this has been a preliminary exercise, taking four specific locations and a model parameterisation for oak and for productive grasslands.

On the basis of the assessment of sensitivity and exposure, it is possible to rank Priority Habitats in terms of the likelihood of adverse effects of ozone, recognising that this is only a preliminary qualitative assessment. However, this assessment is based on current levels of ozone exposure, and it is important to consider how these exposures have changed in the past 20 years, and, more importantly, how they may change in the future. This is considered briefly in *Section 4,* which also considers the potential impact of policies to reduce ozone exposure, and identifies key areas in which the conservation agencies might wish to engage in policy discussions over the next five years. These issues will be considered in much greater depth by three major reports and assessments over the next 2-3 years, and hence detailed analysis is outside of the scope of this report. However, we provide here a brief overview of the key issues, and how these might influence the risk of future ozone impacts on different Priority Habitats.

Finally, *Section 5* provides a brief conclusion to the report and *Section 6* summaries the major recommendations.

2. Sensitivity of terrestrial habitats and positive indicator species to ozone

The data summarised in this chapter are taken from published reviews of ozone impacts on community composition of BAP terrestrial habitats and the sensitivity of relevant 'positive indicator species', as listed in the Common Standards Monitoring Guidance reports (JNCC, 2004a-d, 2006) for National Vegetation Classification (NVC) communities (Rodwell 1991a, 1991b, 1992, 1995, 2000) that form part of each BAP habitat. Positive indicator species (sometimes called 'desirable' or 'characteristic' species in the guidance) are plants whose presence is judged, in nature conservation terms, to be indicative of good habitat condition. It should be noted that the lists do not necessarily include all species typical of a habitat, and lists of positive indicator species are not available for all habitats e.g. woodlands. The majority of species-specific data are taken from the meta-analysis of Hayes *et al*., (2007), who identified 83 plant species from existing publications for inclusion in an ozone sensitivity database (OZOVEG). The relative ozone sensitivity of these species was then assessed based on changes in above-ground biomass. Plant species were ranked in three categories: those showing a reduction in above-ground biomass equivalent to over 10% at 15,000 ppb.h AOT40 compared to 3000 ppb.h (shown in this report as ozone sensitive); those showing no significant change in biomass (ozone insensitive); and those showing a stimulation in above-ground biomass of over 5% at 15,000 ppb.h AOT40 compared to 3000 ppb.h (increased growth in ozone).

Mills *et al*., (2007) used the OZOVEG database to estimate community ozone sensitivity based on broad habitats (European Nature Information System level 4 communities). The number of ozone sensitive and insensitive plant species in the OZOVEG database were compared for each EUNIS community and the ratio of the two was used to estimate the percentage of ozone sensitive species present. A minimum of six studied species within each community was used to increase accuracy with an average of 15.3 species per community present in the database. There is considerable uncertainty associated with scaling-up in this manner. The authors acknowledge that this approach will reflect any tendency of experimenters to report results for species that respond to ozone rather than those that do not and may, as a result, over estimate the percentage of ozone sensitive species present in a community. Additionally, all data were taken from pot-grown plants and no effects of inter- or intra-species competition were included in the calculations. It should also be noted that this application of the OZOVEG database classifies sensitive species as those that respond both positively and negatively to ozone so whilst a habitat with a high proportion of ozone sensitive species may be expected to undergo a shift in community composition, the nature of that shift is impossible to predict. Because of this approach is also impossible to state in this report the predicted percentages of positively and negatively affected species within each community.

Jones *et al*., (2007), also using the OZOVEG database, developed a regression-based model to predict the changes in above-ground biomass caused by ozone in unstudied plant species based on their Ellenberg Indicator values. This model was then applied to the dominant species, weighted by percentage cover, present within 48 NVC grassland communities to produce the predicted ozone sensitivity of each community. The resulting Community Ozone Response Index (CORI) was scaled within a range of 0-10. The calcareous grassland NVC community CG2 was predicted to be the most sensitive to ozone, with a CORI value of 4.75 whilst CG9 grassland was predicted to be the least sensitive with a CORI value of 1.53.

Where CORI values are available for NVC communities occurring in BAP habitats, they are included in this report. As with Mills *et al*., (2007), this scaling-up approach has associated uncertainties. Because CORI values are based on changes in biomass, the co-occurrence of positively and negatively affected species in the same community may cancel each other out, leading to low predicted changes in biomass but concealing real ecological changes in community composition. The cover-weighted approach will also tend to obscure ozone effects on species of high conservation value, which usually occur at low cover and low frequency in a community.

Table 2.1 presents an overview of available data on community sensitivity whilst specific information on different habitats and species responses will be considered in turn during this chapter. When possible, data are presented for Priority Habitats. However, this is not always possible, especially for habitats where small amounts of information are available. In these cases, data are presented for the relevant BAP Broad Habitat. In addition to findings from experimental studies on community sensitivity to ozone, Table 2.1 also includes, where relevant, the estimates of Mills *et al*., (2007) and Jones *et al*., (2007). Proposed changes to the Priority Habitat series resulting from the BAP Priorities Review have not been taken into account here, except for Fens which are divided where possible into lowland and upland. Upland dry acid grasslands are not a BAP Priority Habitat but have also been treated separately where appropriate.

Table 2.1. Summary of published community ozone sensitivity data for BAP habitats.

Broad habitat	Priority habitat	NVC comunity	Community response	Data type	Reference
Broadleaved, Mixed and Yew Woodland		W1-17	56.4% ozone sensitive species	Predicted	Mills *et al*., 2007
			Reduced cover of typical woodland species	Experimental	Ashmore & Keelan 2006
Coniferous woodland		W18	75% ozone sensitive species	Predicted	Mills *et al*., 2007
Acid grassland	Lowland dry acid grassland	U1	Ozone sensitive (CORI: 3.11)	Predicted	Jones *et al*., 2007
		U3	No data		
		U4	Decrease in *Festuca ovina*. Increase in *Agrostis capillaris*	Experimental	Hayes *et al*., 2006
	Upland dry acid grassland	U2	ozone sensitive (CORI: 3.17)	Predicted	Jones *et al*., 2007
		U3, U5, U6	no data		
Calcareous grassland			20% of species show reduction in above-ground biomass and reduction of forbs	Experimental	Warwick & Taylor, 1995
	Lowland calcareous grassland	CG1	*Festuca ovina* biomass reduced by increased ozone	Experimental	Hayes *et al*., 2006
		CG2	ozone sensitive (CORI: 4.75)	Predicted	Jones *et al*., 2007
			Festuca ovina biomass reduced by increased ozone	Experimental	Hayes *et al*., 2006
		CG3	ozone sensitive (CORI: 4.49)	Predicted	Jones *et al*., 2007
			Reduction in dominant spp (*F. rubra*), loss of forbs	Experimental	Thwaites *et al.*, 2006
			Bromus erectus insensitive to ozone	Experimental	Hayes *et al*., 2007
		CG4	No data		
		CG5	*Bromus erectus* insensitive to ozone	Experimental	Hayes *et al*., 2007
		CG6	No data		
		CG7	*Festuca ovina* biomass reduced by increased ozone	Experimental	Hayes *et al*., 2006
		CG8	Ozone insensitive (CORI: 1.56)	Predicted	Jones *et al*., 2007
		CG9	Ozone insensitive (CORI: 1.53)	Predicted	Jones *et al*., 2007

Table 2.1 continued

Calcareous grassland		MG2	No data		
	Upland Calcareous grassland		Shift to *Lollium perenne*. Significant increase in *Alopercurus pratensis*. Significant reductions in *Phleum bertolonii, Briza media*	Experimental	Barnes, 2006
		CG10*	Decrease in percentage cover of *Agrostis capillaris*	Experimental	Hayes *et al*., 2006
		CG9, CG11*, GC12-14	No data		
Neutral grassland	Lowland meadows & Upland hay meadows	MG4	Ozone insensitive (CORI: 1.86)	Predicted	Jones *et al*., 2007
		MG5	Ozone insensitive (CORI: 1.86)	Predicted	Jones *et al*., 2007
		MG3, MG8	No data		
Fen, Marsh and Swamp	Upland Flushes, Fens and Swamps	M4, M5, M7, M8, M9a, M10-13, M29, M31-38, S27	No data		
	Purple Moor Grass and Rush Pastures	M22-26	No data		
	Lowland fens	M1-6, M9 M10, M13, M14, M21-29	No data		
	Reed beds	S4	66.7% ozone sensitive species	Predicted	Mills *et al*., 2007
Bogs	Lowland Raised Bog	M1-3, M17, M19-21	80.4% ozone sensitive species	Predicted	Mills *et al*., 2007
		M18	Reduction in length increment of *Sphagnum* spp	Experimental	Ashmore & Keelan, 2006
	Upland Blanket Bog	M1-3, M17-21	80.4% ozone sensitive species	Predicted	Mills *et al*., 2007
Montane		U12	Ozone insensitive (CORI: 1.67)	Predicted	Jones *et al*., 2007
Inland Rock			No data		
Supralittoral Rock			42% ozone sensitive species	Predicted	Mills *et al*., 2007
Supralittoral Sediment			41.6% ozone sensitive species	Predicted	Mills *et al*., 2007

* Calcareous grassland habitat not on limestone

2.1. Woodlands

For woodland habitats, this report will focus on the impacts of ozone on tree species (Table 2.2), which, generally, show reduced biomass when exposed to high ozone concentrations. The response of sessile and penduncolate oak, silver birch, beech, Norway spruce and Scots pine to increasing AOT40 values was reported by Karlsson *et al*., (2007). This study, which was a synthesis of experiments using young trees, shows that at 10,000 ppb.h., an AOT40 value equivalent to the highest exposures in the UK, there is an annual growth reduction of 10% for birch and beech, 2% for oak and 1.5% for Norway spruce and Scots pine.

However, the results of such studies of individual young trees need to be considered in a broader ecological context. The most detailed recent survey of change in British broadleaf woodlands (Kirby *et al.*, 2005) noted a number of changes in woods of conservation value, including the loss of specialist woodland ground flora species, between 1971 and 2001 in 103 sites within Great Britain. The role of different factors in this change is uncertain. However, Kirby *et al*., (2005) identify the relatively young age of many stands as an important factor and suggest that, without management intervention, British woodlands in general could become older and darker, with detrimental effects on ground flora richness.

In this context, it is of relevance that ozone in general decreases tree growth, reduces leaf area and accelerates leaf ageing and abscission. Hence, effects of ozone on the tree canopy which are detrimental to the trees themselves may actually be beneficial in some circumstances to the ground flora. However, no studies of which we are aware have addressed this issue directly, mainly because ozone is rarely the primary driver of major changes in canopy density and structure in northern and western Europe.

The ranking of species in terms of sensitivity to ozone is primarily based on responses of seedlings or young trees. Less is known of responses of mature trees, although there is some evidence (e.g. for beech and spruce; Nunn *et al.*, 2006) that differences in sensitivity in young trees are lost or reversed when mature trees are considered. There are several mechanisms by which the sensitivity of old trees could be greater than those of younger trees (e.g. a reduced defence capacity, and a finer balance between photosynthesis and respiration), but there is no direct evidence that particularly old and prized individual trees are more sensitive to ozone.

The only feasible experimental approach to assessing whether ozone is having significant effects on woodland canopies and forest stands is through fumigation within the canopy. However, only one such study has been attempted in Europe (Nunn *et al*., 2006). The other approach would be to correlate tree growth, crown condition or other factors with variation in ozone exposure through time and space. Significant correlations between ozone exposure and effects such as reduced growth, changed stand species composition, altered insect herbivore communities, and decline in root vitality have been reported e.g. in the Los Angeles Basin (Arbaugh *et al*., 2003; Jones and Paine, 2006) and central Europe (Braun *et al*., 1999), in regions where ozone levels are well above those in the UK. Significant negative relationships between radial growth of Norway spruce and ozone exposure have been reported in southern Sweden, where ozone exposures are comparable to those in southern Britain (Karlsson *et al*., 2006).

The only specific study using field data of which we are aware in the UK was carried out by Stribley and Ashmore (2002) at Wytham Wood, Oxford. They found significant correlations in time between twig growth patterns of 40 year old beech and both soil moisture deficit and AOT40 exposure; in a compartment with lower soil moisture deficit, ozone exposure had a more significant effect. This study emphasises the difficulty of disentangling the long-term effects of hot summers, in which both drought and ozone stress increase.

Although there are probably thousands of papers on ozone effects on trees, almost all of these have focussed on particular aspects of tree response, and very few have taken an ecosystem approach. The importance of this type of approach is illustrated by the results of seven years of open-air fumigation of an aspen/birch/maple ecosystem in the northern US (Karnosky *et al.*, 2005). This study reports, *inter alia*, effects of ozone in increasing caterpillar and aphid populations, increasing leaf rust infections, decreasing soil mite populations, and decreasing soil microbial activity. Hence, there may be a range of secondary effects of ozone which are important for woodland conservation which have hardly been explored.

A key issue is assessing effects on woodland ground flora is the extent to which ozone concentrations are decreased within the forest canopy. However, the most detailed study of this (Karlsson *et al.,* 2006) on the west coast of Sweden suggests that the reduction in concentrations is on average only 10-15%. A brief study at Grass Wood (Ashmore and Keelan, 2006), a relatively open mixed deciduous wood in the Yorkshire Dales, showed only small decreases within the wood compared with outside, which is consistent with the Karlsson *et al.,* study. Since most woods of high conservation value are likely to have relatively uneven open canopies, reductions in ozone exposures within the canopy may be relatively small compared with dense uniform commercial plantations.

Ashmore and Keelan (2006) investigated the sensitivity to ozone of woodland ground flora species from deciduous woods in the Yorkshire Dales National Park. Mesocosm experiments were conducted by allowing plants to emerge under simulated spring conditions from soil collected from one of the sites. It was found that ozone induced a change in species composition, with the cover and biomass of typical woodland species being reduced compared with non-shade adapted, invasive species. This is shown in Figure 2.1, where plants with low Ellenberg light values were more adversely affected by ozone, in terms of cover and above ground biomass, than those with high values. This result suggests that ozone could have negative effects on typical woodland ground flora. The sensitivity of major spring bulb species is being assessed under the current 'Umbrella' contract by the University of Newcastle.

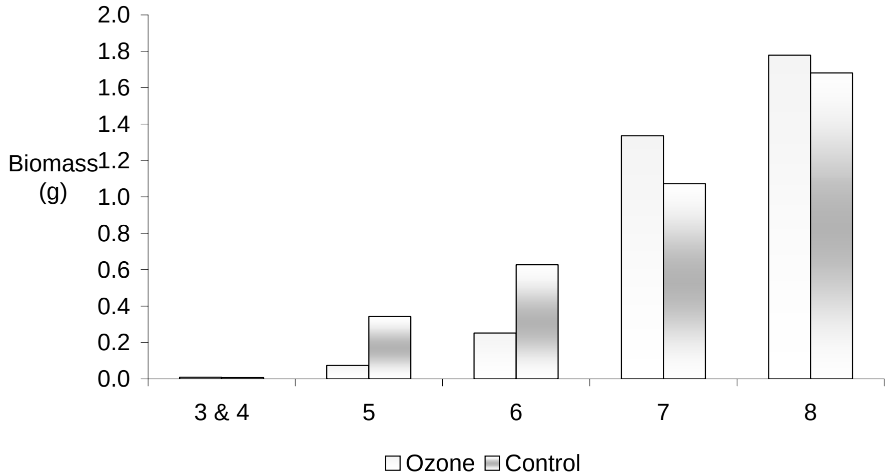


Figure 2.1. Comparison of effects of ozone on above-ground biomass at the end of the experiment for different Ellenberg light classes (3-8) in an ozone fumigation experiment carried out by Ashmore and Keelan (2006).

2.1.1. Broadleaved, Mixed and Yew Woodland

Mills *et al*., (2007) have used the OZOVEG database to estimate that of 126 understorey species (based on EUNIS level 2 classification) found in broadleaved, deciduous woodland, 56% will be either positively or negatively sensitive to ozone.

2.1.1.1. Upland Oakwood

Both sessile (*Quercus petraea*) and penndunculate (*Q. robur*) oak have been classified by Karlsson *et al*., (2007) as less sensitive to ozone than birch or beech. Both *Quercus* species were also classified as being less ozone sensitive than Scots pine. This growth reduction was even greater under drought conditions but was ameliorated by increased CO_2 concentrations. However, in a study in which *Q. petraea* seedlings were fumigated with ozone at concentrations of 57,000-74,000 ppb.h (6 month AOT40), Broadmeadow and Jackson (2000) observed a growth reduction of 30%, twice that of Scots pine under the same treatment. Although there is uncertainty about the relative magnitude of impact, it is clear from the literature that high ozone concentrations will have a negative effect on the growth of oak species.

2.1.1.2. Lowland Beech and Yew Woodland

Beech (*Fagus sylvatica*) has been classified in Karlsson *et al*., (2007) as sensitive and beech saplings showed significantly reduced growth in open top chamber studies carried out by the Forestry Commission where ambient ozone pollution in the range 2000-8000 ppb.h was reduced by filtration (NEGTAP 2001; Figure 2.2).

This sensitivity has been shown by Mansfield *et al*., (2001) to be seasonally variable. Young beech trees showed a significant reduction in the ability to fix carbon when exposed to ozone in the early growing season (mid-May to mid-July) compared to those exposed in late growing season (mid-July to mid-September), which showed little effect on plant growth. The authors also demonstrated that these differences were a function of plant developmental stage and not differing environmental conditions between spring and summer. Importantly, the response to ozone in spring was observed at an AOT40 of 2000 ppb.h, which is well below the generally accepted AOT40 threshold for effects on plant growth. There are no available experimental data on the response of yew (*Taxus baccata*) to ozone.

2.1.1.3. Upland Mixed Ashwoods

There are limited data available on ozone impacts on ash (*Fraxinus excelsior*). Broadmeadow and Jackson (2000) exposed young ash trees to high ozone concentrations (54,000-74,000 ppb.h, 6 month AOT40) and observed no significant effect on growth. It is, therefore, likely that ash is less sensitive to ozone than other major tree species.

2.1.1.4. Wet Woodland

There is limited information for wet woodland tree species. Birch (*Betula pendula*) has been shown to be sensitive to ozone (Karlsson *et al*., 2007; see below) but there are no experimental data available for willow (*Salix cinerea*) or alder (*Alnus glutinosa*). Environmental monitoring programmes have reported that defoliation in alder is positively but non-significantly correlated with increasing ozone exposure (Ozolincius *et al*., 2005).

2.1.1.5. Upland Birchwoods

Young birch trees (*Betula pendula*) have been shown to be sensitive to ozone in several experimental studies carried out using open-topped chambers and at open-field scale (Karlsson *et al*., 2007)

2.1.2. Coniferous woodland

As with broad leaved woodland, this report concentrates on the effects of ozone on tree species within coniferous woodland habitat and, as such, possible community shifts are not discussed. Understorey communities found in coniferous woodland are generally considered to be sensitive to ozone. Mills *et al*., (2007) used the OZOVEG database to predict that 75% of species found in coniferous habitat will be sensitive to ozone. However, the authors note that this prediction is based on experimental testing of only 8 species (of a mean 70 species found in coniferous habitats) and, as such, this result should be treated with caution.

2.1.2.1. Native pine woodlands

Scots pine (*Pinus sylvestris*) has been reported as being sensitive to ozone in several studies (summarised in Karlsson *et al*., 2007; Furher *et al*., 1997). Broadmeadow and Jackson (2000) reported that one year-old Scots pine seedlings exposed to 57,000 – 74,000 ppb.h ozone (6 month AOT40) over the course of the 1994 growing season showed a 15% reduction in growth. This response was exacerbated by drought. This study also investigated the responses of oak and ash and concluded that Scots pine was of intermediate sensitivity, with oak being most sensitive and ash showing no detectable effects. Broadmeadow and Jackson (2000) also conjectured that long-term exposure to high levels of ozone would result in a lack of needle retention, with serious implications for nutrient turnover and carbon balance.

Figure 2.2 shows the results, reported in NEGTAP (2001), of the experimental reduction of ambient ozone pollution using filtration on the growth of tree saplings. Scots pine was less sensitive to ozone than Norway spruce or beech, showing no reduction in height over six years. Whilst the reduction of ozone had no effect on height in Scots pine, the saplings grown in filtered air had improved needle retention. Although juniper is common in native pine woodlands, there are no available data on its sensitivity to ozone.

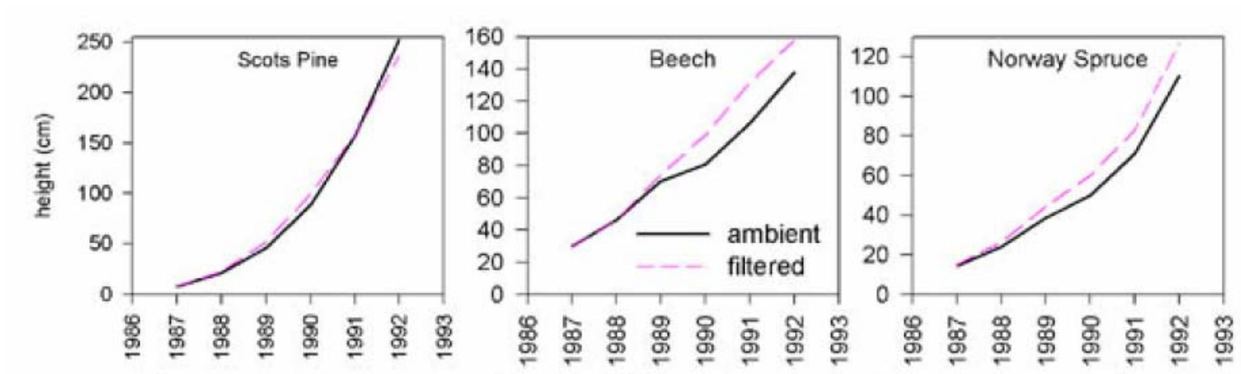


Figure 2.2 Height growth of Scots pine, Beech and Norway spruce after six years growth in ambient or charcoal filtered chambers at Headley in Hampshire (NEGTAP, 2001).

Table 2.2. Summary of published ozone sensitivity data for positive indicator tree species in woodland BAP habitats. “Ozone sensitive” species show a negative response in above-ground biomass to ozone unless stated otherwise

Characteristic species	Priority habitat	Species present in NVC community	Species sensitivity	Reference
Quercus robur	Upland Oakwood	W10, W16	Moderately ozone sensitive	Karlsson *et al.*, 2007
			Moderately ozone sensitive	Furher *et al.*, 1997
Quercus petraea	Upland Oakwood	W11, W16, W17	Moderately ozone sensitive	Karlsson *et al.*, 2007
			Ozone sensitive. Increased sensitivity in drought	Broadmeadow and Jackson, 2000
Fagus sylvatica	Lowland Beech and Yew Woodland	W12, W14, W15	Ozone sensitive	Karlsson *et al.*, 2007
			Ozone sensitive	Mansfield *et al.*, 2001
			Ozone sensitive	Furher *et al.*, 1997
Taxus baccata	Lowland Beech and Yew Woodland	W13	No data	
Fraxinus excelsior	Upland Mixed Ashwoods	W8, W9	Ozone insensitive	Broadmeadow & Jackson, 2000
Alnus glutinosa	Wet Woodland	W5-7	No data	
Salix cinerea	Wet Woodland	W1-3	No data	
Betula pendula	Upland Birchwoods	W4	Ozone sensitive	Karlsson *et al.*, 2007
	Wet Woodland	W5-7		
	Native pine woodlands	W18		
Pinus sylvestris	Native pine woodlands	W18	Moderately ozone sensitive	Karlsson *et al.*, 2007
			Moderately ozone sensitive	Furher *et al.*, 1997
			Ozone sensitive	Broadmeadow & Jackson, 2000
Juniperus communis	Native pine woodlands	W18	No data	

2.2. Grasslands

2.2.1. Acid Grassland

Both lowland and upland acid grasslands are sensitive to ozone, having Community Ozone Response Index (CORI) values of 3.11 and 3.17 respectively placing these communities 5th and 4th most sensitive to ozone (Jones *et al.,* 2007). The slightly higher predicted ozone sensitivity of upland acid grasslands is reflected by Mills *et al.,* (2007), who predict that upland grasslands will contain 68.1% ozone sensitive species, compared to 48.6% in dry lowland grasslands. Whilst acid grasslands have been shown to be sensitive to ozone at the community level, experimental data on the sensitivity of individual species is sparse. All available sensitivity data for positive indicator species are summarised in Table 2.3.

A two year mesocosm study of an upland acid grassland community (U4) was conducted by Hayes *et al.,* (2006), in which simulated communities were fumigated with a range of background (20-45 ppb) and peak (50-1000 ppb) ozone concentrations. There was increased senescence of all plants with the peak ozone treatments, but only subtle changes in community structure, notably an increase in the proportion of *Agrostis capillaris* and a decrease in *Festuca ovina*. There was no visible injury on any of the plants studied, which the authors thought was likely to be partly a result of small, low-growing plants in a dense-canopy community receiving a relatively low absorbed ozone dose.

Of the positive indicator species for acid grasslands, two (*Campanula rotundifolia, Lotus corniculatus*) have been shown to be sensitive to ozone (Ashmore and Keelan 2006; Bungener *et al*., 1999; Hayes *et al*., 2007), one (*Rumex acetosella*) is ozone insensitive (Hayes *et al*., 2007) and two (*Calluna vulgaris, Galium saxatile*) have shown increased growth with increased ozone concentrations (Hayes *et al*., 2007). This highlights the need for increased study of the sensitivity of acid grassland species to ozone and importantly the response of dominant species.

2.2.2. Calcareous Grassland

There have been three major UK ozone exposure experiments on calcareous grassland. Hayes *et al*., (2006) created model CG10 communities and fumigated these with ozone for a growing season. Whilst there was no significant effect on community biomass, there was increased senescence in the dominant grass species *Festuca ovina* and in *Agrostis capillaris* which also displayed decreased percentage cover. In a linked study, plants collected from a lowland calcareous grassland habitat (CG10-12) by Hayes *et al*., (2006) and were exposed, over a 10 week period, to treatments of a continuous background ozone concentration of 30 ppb or a continuous background plus daily peak concentrations of 80-100 ppb. Over half of species in the experiment responded to the peak treatment with leaf injury (e.g. *Carex echinata*), increased leaf senescence (e.g. *Festuca rubra*) or reductions in above-ground biomass (e.g. *Armeria maritima*). There was also a “carry over” effect, where species that did not display any adverse affects during treatment showed affects on biomass after a winter period of ambient ozone exposure (e.g. *Galium saxatile*, *Nardus stricta* and *Saxifraga stellaris*). In a longer-term study, responses to ozone of a species-rich lowland calcareous grassland community (CG3-MG1) over three years were assessed by Thwaites *et al*., (2006). These mesocosms were removed from the Twyford Down site prior to motorway construction. There was a change in community composition (reduction of dominant species, *Festuca rubra*; the loss of forbs such as

Campanula rotundiflolia; and increase in some species: *Galium verum*, *Plantago lanceolata*) over three years with four exposure treatments, including ozone AOT40 values of up to 15,000 ppb.h (Thwaites *et al*., 2006). The authors noted that such communities transplanted from a field site will have been exposed to elevated ozone concentrations for at least two decades, and so may already have been affected. Thus interpretation needs to consider both increases and decreases in ozone exposure in the experimental treatments.

Figure 2.3 shows the change in community composition during an experimental mesocosm study that increased ozone in line with predictions for 2050 over a relatively short period (14 months). There was a suppression of fine grasses of conservation value (*Phleum* and *Briza* spp) in favour of opportunistic species such as *Alopecurus pratensis*, as well as an increase in proportion of the dominant species *Lolium perenne* (Barnes, 2006). These mesocosms were taken from a study to identify management regimes to restore biodiversity in upland grasslands. The direction of the change caused by a relatively small increase in ozone (20ppb in summer; 10ppb in winter) over a short period of time is opposed to that of the management objectives for such communities. It is likely that the long-term effects of ozone on calcareous grasslands will be a result of both the sensitivity of individual species and the response of dominant species.

Whilst there are no data available on community response to ozone specifically for upland calcareous grasslands both upland and lowland habitats contain common positive indicator species that have reduced growth with high ozone concentrations. However, some dominant grass species, such as *Bromus erectus* (Hayes *et al*., 2007), are expected to be relatively insensitive to ozone.

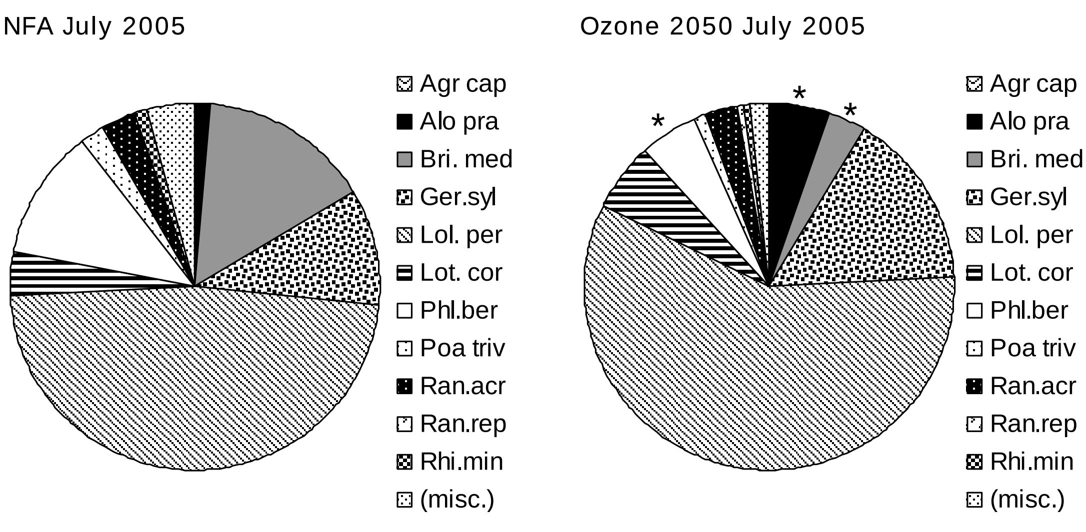


Figure 2.3. Impacts of 14 months' exposure of long-established species rich mesophilic grassland communities to simulated present-day ozone climate versus a predicted 2050 upland ozone climate. Significant shifts in *Alopecurus pratensis, Phleum bertolonii* and *Briza media* denoted by asterisks (Barnes, 2006).

2.2.2.1. Lowland calcareous grassland

Lowland calcareous grassland contains NVC communities that have both the highest (4.49, 4.75) and the lowest (1.53, 1.56) CORI values (Jones *et al*., 2007). In addition, a study of calcareous grassland has shown that 20% of species show a reduction in above-ground productivity (Warwick and Taylor, 1995).

2.2.3. Neutral Grassland

Where they have been studied, lowland and upland hay meadows have not been demonstrated to be sensitive to ozone and NVC communities within the habitats have been calculated to have low CORI values (1.86). Similarly, most data available for positive indicator species within these habitats show that they are either ozone insensitive or have increased growth in ozone (Hayes *et al*., 2007; Ashmore and Keelan, 2006; Bungener *et al*., 1999). The exceptions are the ozone sensitive *Leontodon hispidus* and *Campanula rotundifolia* (Hayes *et al*., 2007; Thwaites *et al*., 2006) and *Lychnis flos-cuculi*, for which information is inconclusive (Hayes *et al*., 2007; Bungener *et al*., 1999). (see Table 2.3 for summarised information). The ozone sensitive species *Valeriana officinalis* occurs as a positive indicator species in the NVC community MG2 but this is considered by CSM guidelines to be a lowland calcareous grassland transition habitat.

Table 2.3. Summary of published ozone sensitivity data for positive indicator species in grassland BAP habitats. "Ozone sensitive" species show a negative response in above-ground biomass to ozone unless stated otherwise.

Positive indicator species	**Priority habitat**	**Species present in NVC community**	**Species sensitivity**	**Reference**
Alchemilla spp.	Lowland calcareous grassland Lowland meadows & upland hay meadows	MG2 MG3, MG5	Increased growth in ozone (*Alchemilla alpina*)	Hayes *et al*., 2007
Alchemilla alpina	Upland calcareous grassland	CG10*, CG11*, CG12, CG13, CG14, U4, U5c	Increased growth in ozone	Hayes *et al*., 2007
Anthyllis vulneraria	Lowland calcareous grassland	CG1, CG2. CG3. CG4. CG5. CG6, CG8	Increased growth in ozone	Hayes *et al*., 2007
Briza media	Upland calcareous grassland	CG9, CG10, CG11, U4, U5c	Ozone insensitive	Hayes *et al*., 2007
Calluna vulgaris	Lowland dry acid grassland, Upland dry acid grassland	U1, U3, U4 U3, U4	Increased growth in ozone	Hayes *et al*., 2007
Campanula rotundifolia	Lowland dry acid grassland, Upland dry acid grassland Lowland calcareous grassland Upland calcareous grassland	U1, U4 U4 CG7, CG9 CG9, CG10, CG10*, CG11*, U4, U5c	Ozone sensitive	Hayes *et al*., 2007
Carex spp.	Lowland calcareous grassland	CG1, CG2, CG7	Increased growth in ozone (*Carex bigelowii*)	Hayes *et al*., 2007
Dianthus deltoids	Lowland calcareous grassland	CG7	Ozone sensitive	Hayes *et al*., 2007
Eupatorium cannabinum	Lowland meadows & upland hay meadows	MG8	Ozone insensitive	Hayes *et al*., 2007
Galium saxatile	Lowland dry acid grassland, Upland dry acid grassland Lowland calcareous grassland	U1, U3, U4 U3, U4 CG7	Increased growth in ozone	Hayes *et al*., 2007

Table 2.3 continued

Leontodon hispidus	Lowland calcareous grassland	CG1, CG2. CG3. CG4. CG5. CG6, CG7, CG9	Ozone sensitive	Hayes *et al*., 2007
	Upland calcareous grassland	CG9, CG10		Hayes *et al*., 2007
	Lowland meadows & upland hay meadows	MG4, MG5		Hayes *et al*., 2007
Lathyrus pratensis	Lowland meadows & upland hay meadows	MG3	Ozone insensitive	Ashmore & Keelan, 2006
Lotus corniculatus	Lowland dry acid grassland,	U1, U4	Ozone insensitive	Hayes *et al*., 2007
	Upland dry acid grassland	U4	Ozone sensitive (reduction of total biomass)	Ashmore & Keelan, 2006
	Lowland calcareous grassland	CG1, CG2. CG3. CG4. CG5. CG6, CG7, CG8 CG9	Ozone sensitive. Worsened with drought	Bungener *et al*., 1999
	Upland calcareous grassland	CG9, CG10, CG11, CG12, CG13, CG14, U5, U4c		
	Lowland meadows & upland hay meadows	MG3, MG4, MG5		
Lychnis flos-cuculi	Lowland meadows & upland hay meadows	MG8	Ozone sensitive	Hayes *et al*., 2007
			Ozone insensitive	Batty *et al*., 2001
			Ozone insensitive in wet conditions. Increased growth in dry conditions	Bungener *et al*., 1999
Rumex acetosella	Upland dry acid grassland	U4	Ozone insensitive	Hayes *et al*., 2007
	Lowland calcareous grassland	CG7	Ozone sensitive (reduction of below-ground biomass)	Batty *et al*., 2001
Silene acaulis	Upland calcareous grassland	CG12, CG13, CG14	Ozone sensitive	Hayes *et al*., 2007
Valeriana officinalis	Lowland calcareous grassland	MG2	Ozone sensitive	Hayes *et al*., 2007
			Ozone sensitive (reduction of below-ground biomass)	Ashmore & Keelan, 2006

2.3. Wetlands

2.3.1. Fen, marsh and swamp

Whilst there are no experimental data available on the possible effects of raised ozone concentrations on priority habitats within the Fen, Marsh and Swamp classification, Mills *et al*., (2007) have estimated that wetland habitats will contain relatively high proportions of ozone sensitive species (Table 2.4). These predictions should be treated with some caution in the case of reed beds as they are based on only a small number of test species. There is a small amount of experimental and predictive data published for individual positive indicator species with several species (*Filipendula ulmaria, Leontodon hispidus* and *Valeriana officinalis*) showing negative responses to ozone. It is worth noting that there is occasional disagreement between experimental responses to raised ozone and predicted sensitivity, with *Lychnis flos-cuculi* classified as ozone sensitive in the OZOVEG database but showed no significant reduction in biomass when exposed to a six month AOT40 of 9300 ppb.h (Batty *et al*., 2001). Conversely, *Eupatorium cannabinum* and *Rumex acetosa* are reported by Hayes *et al*., (2007) to be ozone insensitive, whilst some studies show significant biomass reduction when fumigated with ozone. In particular, *Eupatorium cannabinum* showed a 10% reduction in biomass at an AOT40 of only 2888 ppb.h (Batty *et al*., 2001).

2.3.2. Bogs

The only positive indicator species for bogs that have been assessed for ozone sensitivity are *Calluna vulgaris* and *Carex bigelowii* (Table 2.4), which are insensitive to increasing ozone concentrations when above-ground biomass was used as the criterion (Hayes *et al*., 2007) although *Calluna* has demonstrated increased susceptibility to damage from natural frosting episodes when fumigated with ozone (Foot *et al*., 1997). The only study of bog community responses to ozone has been conducted by Toet, reported in Ashmore and Keelan (2006). This showed no significant effect on the community composition of lowland raised bog using mesocosms transplanted from a site in south Cumbria. However, it is worth noting that, whilst there was no significant effect of increased ozone over the course of a single year (75 ppb above ambient in summer; 10 ppb in winter) there was a non-significant tendency for ozone to have a substantial negative impact on length increment of *Sphagnum* during the winter. There was also evidence that ozone reduced methane emissions in summer, suggesting an effect on below-ground processes. It is suggested that further studies of bog communities are essential to evaluate the longer-term effects on this community.

Table 2.4. Summary of published ozone sensitivity data for positive indicator species in wetland BAP habitats. "Ozone sensitive" species show a negative response in above-ground biomass to ozone unless stated otherwise

Positive indicator species	Priority habitat	Species present in NVC community	Species sensitivity	Reference
Calluna vulgaris	Purple Moor Grass and Rush Pastures	M24	Increased growth in ozone	Hayes *et al*., 2007
	Lowland fens	M21, M24		
	Lowland Raised Bog	M2		
	Upland Blanket Bog	M2		
Eupatorium cannabinum	Lowland fens	M22, M24	Ozone insensitive	Hayes *et al*., 2007
			Ozone sensitive	Batty *et al*., 2001
Filipendula ulmaria	Lowland fens	M24-28	Ozone sensitive	Batty *et al*., 2001
			Ozone sensitive	Batty *et al*., 2001
Iris pseudacorus	Lowland fens	M28	Ozone insensitive	Batty *et al*., 2001
Leontodon hispidus	Lowland fens	M26	Ozone sensitive	Hayes *et al*., 2007
Lychnis flos-cuculi	Purple Moor Grass and Rush Pastures	M22, M23, M26	Ozone sensitive	Hayes *et al*., 2007
	Lowland fens	M5, M22, M23, M26	Ozone insensitive	Batty *et al*., 2001
			Ozone insensitive in wet conditions. Increased growth in dry conditions	Bungener *et al*., 1999
Mentha aquatica	Upland Flushes, Fens and Swamps (proposed PH)	M8, M9b, M13, S27	Increased growth in ozone	Batty *et al*., 2001
	Purple Moor Grass and Rush Pastures	M22, M23, M25		
Rumex acetosa	Lowland fens	M4	Ozone insensitive	Hayes *et al*., 2007
			Ozone sensitive (below-ground biomass)	Batty *et al*., 2001
Valeriana officinalis	Purple Moor Grass and Rush Pastures	M25, M26	Ozone sensitive	Hayes *et al*., 2007
	Lowland fens	M25, M26	Ozone sensitive	Batty *et al*., 2001

2.4. Heath

There are no experimental data currently available on the possible community responses of Dwarf Shrub Heath to ozone, but Mills *et al*., (2007) have estimated that lowland shrub heathland contains 51.7% ozone sensitive species. Mills *et al*., (2007) have estimated that Arctic, Alpine and Sub-alpine scrub will contain a considerably greater proportion of ozone sensitive species (72.4%). Whilst this may be an overestimate for upland heath in the UK, it is probable that these habitats will be more sensitive to ozone than their lowland counterparts. Because these estimates include both positive and negative sensitivity, predictions of likely ozone impacts to heathland are impossible. There are some experimental data for common heath species (Table 2.5), all of which are either insensitive to ozone or show increased growth. Thus far, no positive indicator species exhibiting negative ozone sensitivity have been identified, highlighting the need for further research in assessing possible negative impacts on less common heath flora.

2.5. Montane

Upland bog habitats have been included here as montane habitats, for a more detailed discussion of upland wetlands, refer to Section 2.3. Upland grasslands occurring at high altitudes are discussed in Section 2.2. Whilst the NVC type U12 has been predicted by Jones *et al*., (2007) to be relatively ozone insensitive, the montane classification represents a heterogeneous range of habitats and this should not be used to draw wider conclusions. It is interesting to note that of the positive montane indicator species for which ozone sensitivity has been evaluated, all are common species that respond to increased ozone concentrations with increased growth (Table 2.6). It is possible, therefore, that increasing ozone could lead to an increased proportion of these species in montane habitats.

2.6. Inland Rock

There is an extremely limited data set available for inland rock habitats (Table 2.6). The only available study on limestone pavement observed no adverse effects from ozone fumigation to plant species grown from seed collected from limestone pavement SSSIs in the Yorkshire Dales National Park (Ashmore and Keelan, 2006). Species studied were *Centurea nigra*, *Geranium robertianum*, *Lotus corniculatus*, *Serratula tinctoria* and *Solidago virgrea*. Interestingly, populations of *Lotus corniculatus* in this study differed from those exposed to ozone in calcareous grassland habitats, which displayed significant reductions in biomass (see section 2.2). The authors concluded that limestone pavement habitats may be less responsive to ozone.

2.7. Supralittoral Rock and Supralittoral Sediment

No positive indicator species are available for supralittoral habitats. However, both supralittoral rock and supralittoral sediment (specifically coastal dunes and sandy shores) have been predicted to contain about 42% ozone sensitive species respectively (Mills *et al*., 2007). Because *Festuca rubra-Galium verum* fixed dune grassland is often indicative of machair (BAP website), the sensitivity of *F. rubra* to ozone (Hayes *et al*., 2007) has been included in Table 2.6.

Table 2.5. Summary of published ozone sensitivity data for positive indicator species in heath BAP habitats. "Ozone sensitive" species show a negative response in above-ground biomass to ozone unless stated otherwise

Positive indicator species	Priority habitat	Species present in NVC community	Species sensitivity	Reference
Calluna vulgaris	Lowland Heathland	H1-12, M14-16	Increased growth in ozone	Hayes *et al*., 2007
	Upland Heathland	H4, H5 H7-10, H12, H16, H18, H21, H22, M14-16		
Carex spp.	Lowland Heathland	H1-4 H6-12, M14	Increased growth in ozone (*Carex bigelowii*)	Hayes *et al*., 2007
Festuca spp.	Lowland Heathland	H1-4 H6-12, M14	Increased growth in ozone (*Festuca pratensis*)	Hayes *et al*., 2007
		H1-4 H6-12, M14	Ozone insensitive (*Festuca rubra*)	Hayes *et al*., 2007
Lotus corniculatus,	Lowland Heathland	H1-4 H6-12, M14	Ozone insensitive	Hayes *et al*., 2007
Plantago lanceolata	Lowland Heathland	H1-4 H6-12, M14	Ozone insensitive	Hayes *et al*., 2007
Vaccinium spp.	Upland Heathland	H4, H7-10, H12, H16, H18, H21, H22, M14	Increased growth in ozone (*Vaccinium vitis-idaea*)	Hayes *et al*., 2007

Table 2.6. Summary of published ozone sensitivity data for positive indicator species in montane, inland rock, and coastal BAP habitats. "Ozone sensitive" species show a negative response in above-ground biomass to ozone unless stated otherwise

Characteristic species	Priority habitat	Species present in NVC community	Species sensitivity	Reference
Alchemilla alpina	Montane	U7, U8, U11-13	Increased growth in ozone	Hayes *et al*., 2007
Calluna vulgaris	Montane	H13-15, 17, 19, 20, 22, M1-3, M17-21	Increased growth in ozone	Hayes *et al*., 2007
Carex bigelowii	Montane	M1-3, M17-21	Increased growth in ozone	Hayes *et al*., 2007
Centarea nigra	Limestone Pavement		Ozone insensitive	Ashmore & Keelan, 2006
Festuca rubra	Machair		Ozone insensitive	Hayes *et al*., 2007
Geranium robertanium	Limestone Pavement		no significant effect	Ashmore & Keelan, 2006
Lotus corniculatus	Limestone Pavement		Ozone insensitive	Hayes *et al*., 2007
			Ozone insensitive	Ashmore & Keelan, 2006
Serratula tinctoria	Limestone Pavement		Ozone insensitive	Ashmore & Keelan, 2006
Solidago virgaurea	Limestone Pavement		Ozone insensitive	Ashmore & Keelan, 2006
Salix herbacea	Montane	U14	Increased growth in ozone	Hayes *et al*., 2007
Vaccinium vitis-idaea	Montane	H13-15, 17, 19, 20, 22	Increased growth in ozone	Hayes *et al*., 2007

2.8. Sensitivity of BAP Priority Species

In addition to the Priority Habitats, a large number of individual Priority Species have also been identified in the UK BAP. A literature search was conducted to identify if the ozone sensitivity of any of these Priority Species had been assessed, but no references were found. This presumably reflects the difficulty of accessing adequate seed or plant material of small and threatened populations. The only study of which we are aware that examined rare or vulnerable species was that of Thwaites (1996), who fumigated ten such species with ozone. A number of these species were found to be relatively sensitive to ozone, including *Anisantha madritensis*, *Lotus angustissimus*, *Phleum phleoides*, *Tetragonolobus maritimus*, *Trifolium incarnatum* and *Trifolium strictum*, all which displayed significant damage when exposed to ozone concentrations of 80 ppb.

Priority Species include plant and animal species. These could be threatened directly by effects of ozone, or indirectly through effects on community composition or host species for invertebrates. Thus a more detailed analysis of the potential risk to Priority Species, including their distribution in relation to ozone concentrations, their specific habitat requirements, and their predicted ozone sensitivity, could be useful in identifying individual species which are potentially at risk, and which should be investigated in more detail.

3. Exposure Assessment

3.1. Ozone exposure of BAP habitats

To assess the risk of ozone impacts to BAP habitats, it is essential to have a measure of habitat exposure to ozone. In this section, the distributions of BAP Priority Habitats in England, Scotland and Wales are compared with six month AOT40 distributions, relevant to all forest and perennial dominated communities, and the percentage of the total area of each habitat falling within areas where critical level exceedence is likely are estimated. Ozone exposure classes were ranked as low (AOT40 <4750 ppb.h), moderate (AOT40 4750-6500 ppb.h) and high (AOT40 >6500 ppb.h). Ozone exposure data were supplied by Coyle *et al*., (pers. comm.) who used measurements of ozone and NO_x concentrations from 20 well-distributed rural sites to identify major variables controlling surface ozone concentrations and to interpolate six-month (April-September) AOT40 distributions across the UK for the period 1999-2003 (Figure 3.1). BAP habitat distributions were supplied separately for England, Scotland and Wales. English BAP data were supplied in digital format from English Nature and Scottish and Welsh data were taken from published sources (Scotland: Ellis and Munro 2004; Wales: Jones *et al*., 2003). It should be emphasised that the maps of AOT40 exposure only indicate broad spatial trends, because of the limited number of sites. There is considerable uncertainty in the assessment, and the maps should not be used to infer the exposure of a particular site.

The percentage of total national area of each habitat occurring in each AOT40 class was calculated for England using GIS to overlay the two data sets. Because the AOT40 distribution data were supplied at a low resolution, there is some uncertainty associated with classifying the ozone exposure of habitats occurring at the edges of AOT40 zones, however this approach still allowed a relatively accurate estimate. The percentage of total habitat area occurring in the moderate classes represents the proportion of habitat where critical AOT40 levels are likely to be exceeded and these percentages, as well as percentage area exposed to high AOT40s, where critical levels are expected to be exceeded, are shown in Table 3.1. Where habitat distribution data are not available habitats are not reported. AOT40 distributions were compared, with a lower level of accuracy than for England, to the national distribution of each priority habitat for Scotland and Wales to derive approximate estimates of the percentage of habitats (in the classes 0, <1, 1-10, 10-25, 25-50, >75) in moderate and high AOT40 zones. Because these values were not calculated using GIS, it is not appropriate to sum estimates of habitat distribution in each AOT40 class, but estimates for each AOT40 class are shown in Tables 3.2 and 3.3 respectively and it is possible to assess the relative ozone risk to each habitat in Scotland and Wales. Because all AOT40 values in Northern Ireland are below 4750 ppb.h and BAP habitats are therefore apparently not exposed to ozone above current critical levels, these are not included in this analysis. However, AOT40 values for Northern Ireland are based on a single monitoring site (Lough Navar), emphasising the need for increased ozone monitoring in this region.

In England, habitats that have distributions concentrated in the south-east are generally exposed to the greatest AOT40 values and eight Priority Habitats have over half of their total national area exposed to high AOT40 values. Lowland calcareous grassland has the greatest exposure, with approximately 97% of all habitat areas being exposed to AOT40 values of

4750 ppb.h or above. However, all priority habitats for which distribution data were available could be said to be at risk from ozone exposure. All habitats, with exception of lowland raised bogs, have more than 80% of their total area exposed to AOT40 values of 4750 ppb.h or greater.

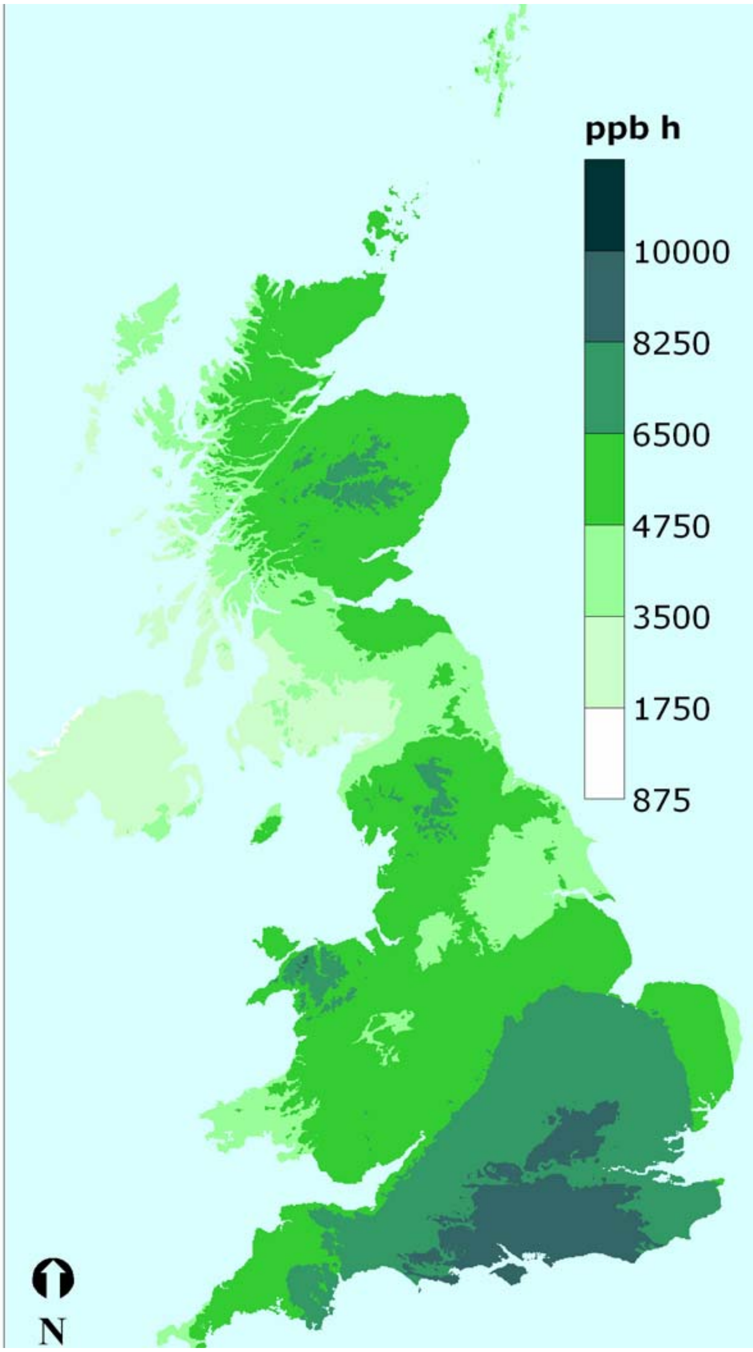


Figure 3.1. 1999 to 2003 average Apr-Sep AOT40 values in Britain (Coyle pers. comm.)

Table 3.1. Percentage of BAP priority habitats in England occurring within areas of moderate and high and ozone exposure, ranked by percentage of total habitat area exposed to AOT40 > 6500 ppb.h.

Priority habitat	**% habitat with moderate or high exposure (>4750 ppb.h)**	**% habitat with high exposure: >6500 ppb.h**
Lowland calcareous grassland	97	72
Wet woodland	94	65
Lowland meadow	90	64
Lowland mixed deciduous woodland	94	60
Fens	88	60
Lowland beech and yew woodland	92	59
Reedbed	83	57
Lowland heath	88	56
Coastal and Floodplain Grazing Marsh	82	48
Purple moor grass and rush pastures	93	38
Upland oakwood	96	31
Lowland dry acid grassland	92	26
Upland hay meadows	80	26
Upland mixed ashwoods	89	25
Upland calcareous grassland	89	23
Upland heath	93	17
Lowland raised bog	34	4

Table 3.2. Estimated percentage of BAP priority habitats in Scotland occurring within areas of moderate and high ozone exposure, ranked by percentage of total habitat area exposed to AOT40 > 6500 ppb.h.

Priority habitat	**% habitat with moderate exposure: 4750-6500 ppb.h**	**% habitat with high exposure: >6500 ppb.h**
Upland oakwood	25-50	10-25
Native pine woodlands	25-50	10-25
Upland calcareous grassland	25-50	10-25
Wood pasture and parkland	25-50	1-10
Upland and lowland heath	25-50	1-10
Upland mixed ashwoods	25-50	1-10
Wet woodland	10-25	1-10
Lowland dry acid grassland	10-25	1-10
Upland hay meadows	>75	<1
Lowland meadows	10-25	<1
Purple moor grass and rush pastures	10-25	<1
Lowland calcareous grassland	25-50	0
Coastal sand dune	25-50	0
Blanket bog	25-50	0
Limestone pavement	25-50	0
Coastal vegetated shingle	25-50	0
Machair	10-25	0
Lowland raised bog	1-10	0

Table 3.3. Estimated percentage of BAP priority habitats in Wales occurring within areas of moderate and high ozone exposure ranked by percentage of total habitat area exposed to AOT40 > 6500 ppb.h.

Priority habitat	% habitat with moderate exposure: 4750-6500 ppb.h	% habitat with high exposure: >6500 ppb.h
Blanket bog	50-75	25-50
Upland calcareous grassland	>75	10-25
Lowland heath	>75	10-25
Upland heath	>75	10-25
Upland fen	>75	10-25
Lowland fen	>75	10-25
Upland oakwood	>75	1-10
Wet woodland	>75	1-10
Upland mixed ashwoods	>75	1-10
Lowland dry acid grassland	>75	1-10
Lowland meadows	>75	1-10
Purple moor grass and rush pastures	50-75	1-10
Wood pasture and parkland	>75	<1
Lowland beech and yew	>75	<1
Reedbed	>75	<1
Lowland raised bog	>75	<1
Lowland calcareous grassland	>75	0
Limestone pavement	>75	0

Scotland has a lower proportion of the country exposed to high AOT40 values and, as such, no BAP priority habitat has more than 25% of total area exposed to AOT40 values greater than 6500 ppb.h. Upland oakwood, Upland calcareous grassland and Native Pine woodlands have the highest percentage of total habitat in areas of high ozone exposure.

High AOT40 areas in Wales are restricted to Snowdonia and only blanket bog has large proportions of total habitat in areas with AOT40 values of 6500 ppb.h or greater. However, the majority of Wales falls within the moderate ozone exposure class and, as a result, all Priority Habitats apart from Purple moor grass and rush pastures have over 75% of their total area exposed to moderate levels of ozone. In particular, nearly all blanket bog habitats in Wales occur in areas of moderate or high AOT40 meaning that there is the potential for large ozone impacts on this habitat.

It should be stressed that the data presented here are approximate figures intended to provide an indication of the relative risk of BAP habitats to ozone exposure. For definitive information on the AOT40 exposure of priority habitats it is recommended that a detailed geographical analysis is carried out.

3.2. Vulnerability of BAP habitats

Whilst it is beyond the remit of this report to carry out a formal analysis and ranking of the ozone sensitivity of BAP habitats it may be useful to briefly consider the relative risk of habitats based on their sensitivity, as discussed in Section 2, and exposure of the communities discussed in this section, in order to identify possible high risk habitats. The relative risk of ozone impacts to BAP habitats is discussed by country. Within England, most habitats have large (>80%) percentages of their total distribution in areas where critical levels for ozone are likely to be exceeded. Lowland calcareous grassland has the greatest percentage of total area exposed to high AOT40 and it is reasonable to assume that ozone impacts on these communities will be high. However, CORI values calculated by Jones *et al*., (2007) for NVC communities occurring within this habitat are amongst the highest (CG2, CG3) and lowest (CG8, CG9) of all 48 communities assessed. Of these, CG3 communities are largely found in south-east lowland areas whilst CG8 and CG9 are generally restricted to northern England. It is likely, therefore that calcareous grasslands in south-east England will not only be exposed to very high ozone concentrations, but also contain the most ozone sensitive communities putting them at a very high risk of ozone impacts. This community level difference in ozone sensitivity within a BAP priority habitat demonstrates that further risk analysis to NVC community level may be useful in some instances. Acid grasslands are also estimated by Jones *et al*., (2007) to be of a similar sensitivity to calcareous grasslands, however, a far lower proportion (26% for acid, 72% for calcareous grasslands) of these habitats occurs in areas of high ozone exposure meaning that vulnerability is likely to be lower. Of woodland habitats, most at risk are upland oak and wet woodlands, which have the highest exposure and are also sensitive to ozone. Beech and Yew woodlands have a relatively high exposure to ozone (>90% in moderate to high exposure) and are also ozone sensitive, putting them at high risk of ozone impacts. At lowest risk are lowland raised bog (which has a low percentage of exposure to high AOT40) and upland heath and inland rock habitats, which have relatively low exposure and low ozone sensitivity.

In Scotland, upland oak and pine woods have a similar (up to 75%) proportion of total distribution in areas of moderate and high exposure. It is estimated by Mills *et al*., 2007) that coniferous habitats will contain a larger number of ozone sensitive species (75%) than broadleaved habitats (56.4%), and Scots pine is relatively sensitive to ozone, so it is possible that Native pine woodlands will be more vulnerable to ozone impacts than Upland oakwoods. This analysis does not take account of the possible effects of changing tree structure on ground flora. Upland habitats in Scotland are, generally, at greater risk from ozone impacts than lowland habitats meaning that acid grassland, which is predicted to be sensitive to ozone, in these areas is also at high risk.

It is interesting to note that whilst upland blanket bogs are predicted to be relatively ozone insensitive by Jones *et al.,* (2007) they are also estimated to contain a high proportion (80%) of ozone sensitive species, including those with a positive response (Mills *et al.,* 2007). This apparent discrepancy highlights the lack of direct experimental data available for wetland species. This is especially pressing as high ozone concentrations are more likely to occur in upland areas and the majority of blanket bog in Wales occurs in these areas. It is possible, therefore, that upland wetlands are among the habitats most likely to undergo a shift in community composition. In general, upland areas will continue to be exposed to high ozone concentrations and habitats in these areas, in Scotland and Wales, will be at greater risk than those in the lowlands.

3.3. Impacts of ozone using flux modelling

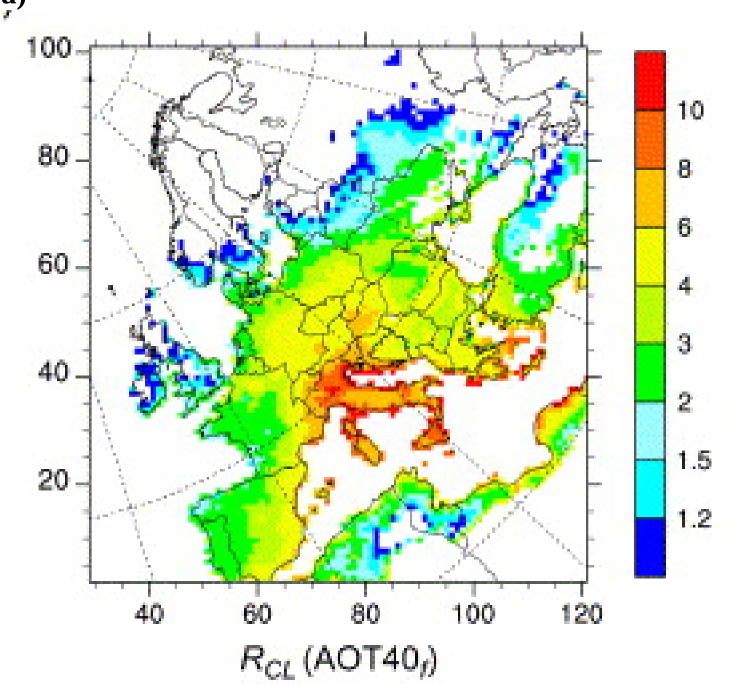
3.3.1. AOT40 and ozone flux approaches

For the last decade the primary measure for assessing ozone risk to vegetation has been the AOT40 index, with the critical level for perennial-dominated communities set at 5000 ppb.h over a growing period of six months (see Section 1.3). However, the AOT40 approach does not take account of the effect of external factors, such as climate and growth stage, on stomatal uptake of ozone. For example, stomatal fluxes of ozone in warm, humid conditions with moist soil can be much greater than hot, dry conditions with dry soil because stomata will be open for greater time periods. There is a growing body of evidence to suggest that, rather than using external concentrations, ozone impacts are better estimated using a measure of ozone absorbed into plant tissue via stomata. To assess the impact of ozone over the course of the growing season, the accumulated ozone flux over a critical threshold can be calculated in a manner analogous to the AOT40 approach to produce the ozone uptake measure $AF_{st}Y$, where Y is a critical flux threshold above which ozone effects become significant. Critical flux thresholds are currently set at 6 nmol O_3 m^{-2} PLA s^{-1} (Projected Leaf Area; the area of leaves that are projected towards the sun) for crops and 1.6 nmol O_3 m^{-2} PLA s^{-1} for forest trees (CLRTAP, 2006).

The Deposition of Ozone and Stomatal Exchange (DO_3SE) model has been developed to assess ozone risks based on cumulative stomatal flux (Emberson *et al.*, 2000, 2001; Simpson *et al.*, 2003; Ashmore *et al.*, 2004). The DO_3SE model is a multiplicative stomatal conductance model where stomatal conductance is calculated as a product of phenology, light, vapour pressure deficit (VPD) and soil water potential (SWP). Detailed stomatal flux and deposition algorithms have been developed for major arable and forest tree species and for *Lolium perenne* dominated grassland.

As an example of the contrast between AOT40- and flux-based approaches, Figure 3.1 shows maps of ozone exposure to forests in Europe calculated by Simpson *et al.,* (2007) using the DO_3SE model. Figure 3.1a shows the relative exceedence (R_{CL}) for AOT40 and Figure 3.2b shows the R_{CL} of $AF_{st}Y$. The relative exceedance gives the ratio of the modelled AOT40 value to the critical level, so a value below 1 indicates that the critical level is not exceeded, while a value of 2 indicates that the modelled value is twice the critical level. The AOT40 approach shows a clear north-south gradient, with high R_{CL} values around the Mediterranean coast decreasing steadily towards northern Europe. The R_{CL} of $AF_{st}Y$, on the other hand, not only shows a much smaller range across Europe but also generally higher values, and thus higher risk, across most of the continent and, particularly, in the UK.

a)



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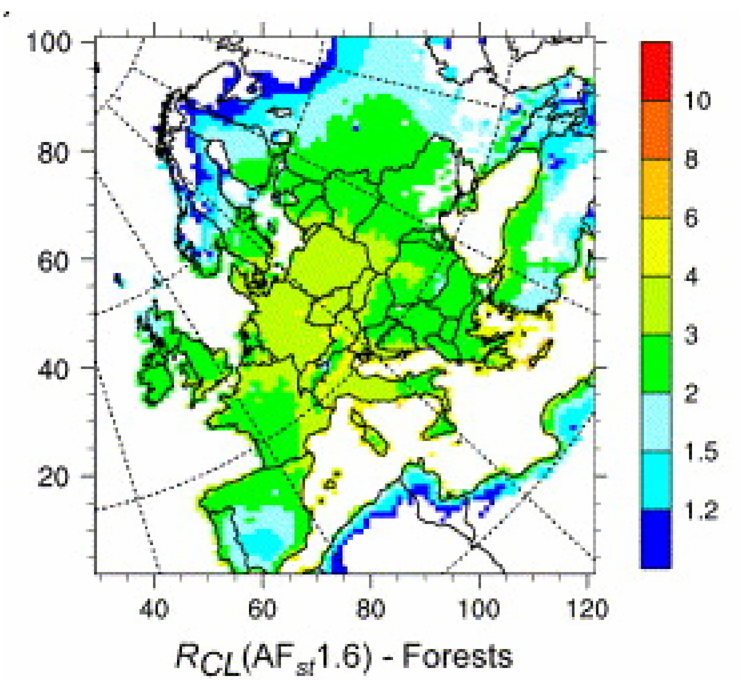


Figure 3.1 Relative exceedence of a)AOT40 and b) AFst1.6 for European forests in 2000 (Simpson *et al*., 2007)

3.3.2. Potential impacts of ozone flux to BAP habitats

The DO_3SE model has not yet been used to estimate ozone fluxes to natural and semi-natural communities and in this section an initial comparison of $AF_{st}Y$ and AOT40 values is carried out. The DO_3SE model is used to compare modelled $AF_{st}Y$ values with modelled AOT40 values in four areas the UK. It should be stressed that the data presented here are based on large-scale modelled data and represent an initial illustration of the possible seasonal differences in ozone impacts on habitats, and the AOT40 values differ from those based on interpolations of national monitoring data which were presented in Section 3.1. To compare the AOT40 and ozone flux approaches for natural habitats, accumulated ozone fluxes over a six month period (April-September) are compared to AOT40 values for the same period.

Meteorological and ozone concentration data have been taken from the EMEP unified model (Simpson *et al*., 2003) and used to calculate ozone fluxes. Variables from the EMEP model are calculated on a 50 x 50 km, Europe-wide grid. Because of time limitations, only four EMEP grid squares from the UK (Table 3.4) have been used to compare $AF_{st}Y$ and AOT40. Within each grid square, $AF_{st}Y$ has been calculated for grass and for oak. $AF_{st}Y$ values for oak were calculated using an oak parameterisation for the DO_3SE model (Aranda *et al*., 2002; Raftoyannis and Radoglou, 2002; Heath *et al*., 1998; Vivin *et al*., 1993). For grasslands, the DO_3SE model was used with a parameterisation based on *Lolium perenne* (Ashmore at al. 2007) with a UK climate specific modification. For calculation of ozone fluxes in grasslands the DO_3SE model was coupled with a grassland growth model with the capacity to simulate morphological and physiological processes of temperate grass growth (Eatherall *et al*., 1993; Terry and Woodward, 1994).

Table 3.4. EMEP grid squares in Britain used for ozone flux calculation.

Country	Area	EMEP grid reference	Centre of Square (OS reference)
England	New Forest	85,48	SU251106
England	Nottinghamshire	84,53	SK580396
Scotland	Argyll	76,57	NN321173
Wales	Snowdonia	81,51	SJ005513

Figures 3.2 and 3.3 show the increase in AOT40 and $AF_{st}Y$ values over the growing season for oak and grass during the modelled period in each selected area. The levelling off of $AF_{st}Y$ values observed for grass in the second half of the modelled period is caused by increasing SMD causing a reduction in stomatal conductance below the critical threshold. Whilst AOT40 and $AF_{st}Y$ are not directly comparable, it is interesting to compare their relative values in the four locations (Table 3.5). The final AOT40 values follow the expected north-south gradient; ozone exposure decreases with increasing latitude (e.g. New Forest > Nottinghamshire > Snowdonia > Argyll) and the English areas have substantially larger AOT40s than those in Scotland and Wales. This relationship is not, however, reflected in the modelled $AF_{st}Y$ data and, similar to Simpson *et al*., (2007), oak $AF_{st}Y$ modelling shows a substantial departure from AOT40. The New Forest is still the area of highest ozone exposure but Snowdonia is the second highest and Argyll the third, with Nottinghamshire having the lowest value. For grass the difference is even more striking, the greatest uptake of ozone is seen in Snowdonia, followed by Argyll then New Forest and finally Nottinghamshire, an almost complete reversal of the trend predicted using AOT40.

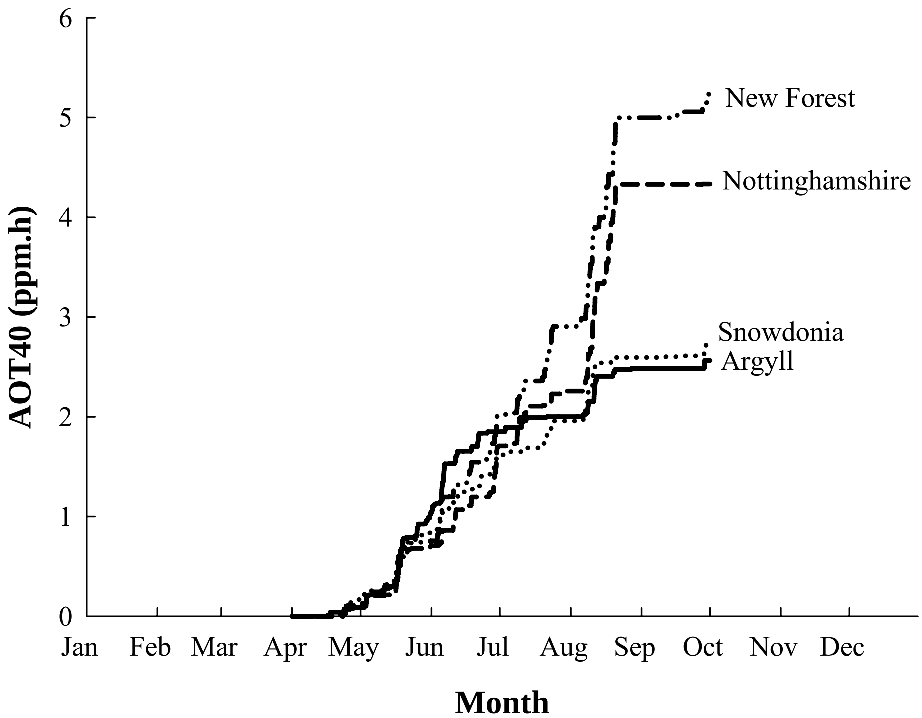
The AOT40-based risk assessment of ozone exposure to BAP habitats, such as the one carried out in the previous section, would conclude that the greatest risk to vegetation occurs in south-east England and British uplands. However, the examples given in this section show that a flux-based approach, which would assess the actual uptake of ozone by plants, may produce a substantially different distribution map of ozone risk, implying much higher impacts in Scotland and Wales. No grid square covering Northern Ireland was included in this analysis but it is possible that a flux-based assessment would indicate a greater risk of ozone impacts than the current AOT40 approach.

It must be stressed that the ozone flux modelling carried out in this section is an example of the contrasting natures of the AOT40- and flux-based approaches to evaluating ozone risk. A full and rigorous analysis of ozone fluxes to BAP habitats would require a full parameterisation of the DO_3SE model for a range of relevant species based on field data.

Table 3.5. Final AOT40 and $AF_{st}Y$ values for grass and oak in selected areas of the UK.

		Snowdonia	**Nottinghamshire**	**New Forest**	**Argyll**
grass	AOT40 (ppb.h)	2800	4400	5300	2600
	$AF_{st}6$ (mmol m^{-2})	6.8	4.5	5.8	6.4
oak	AOT40 (ppb.h)	2800	4400	5300	2600
	$AF_{st}1.6$ (mmol m^{-2})	16.6	11.3	20.5	15.6

a)



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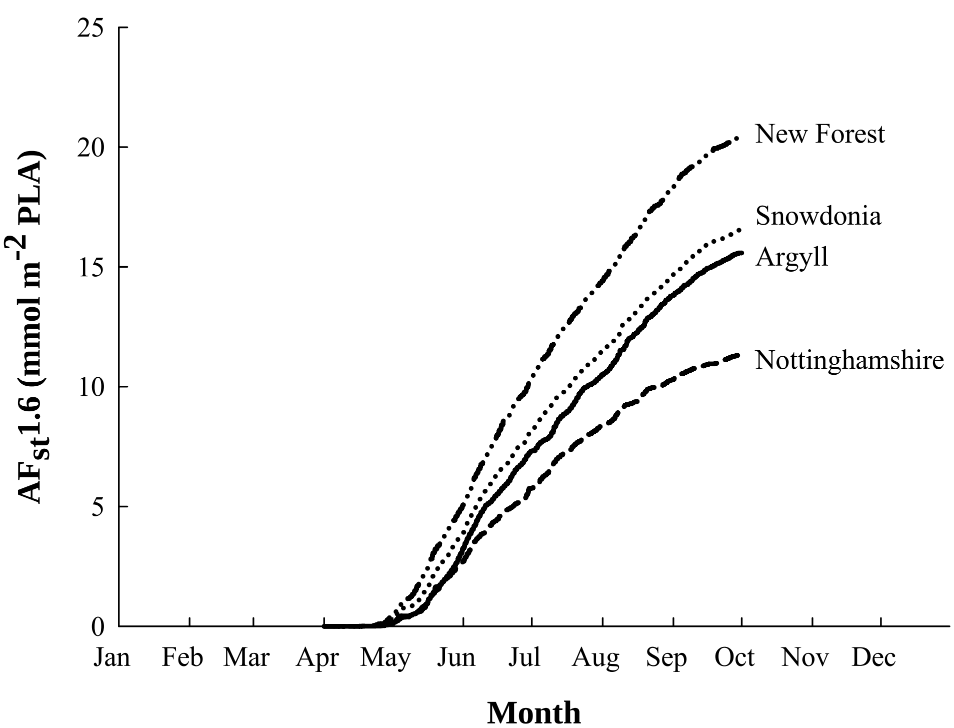
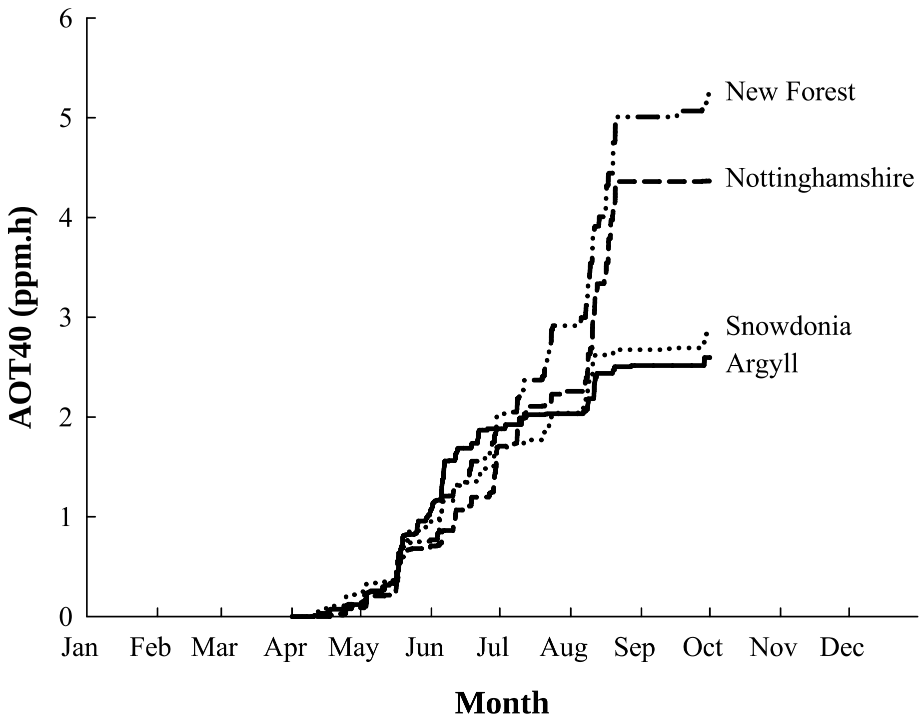


Figure 3.2. a) AOT40 and b) $AF_{st}1.6$ for oak in selected areas in the UK.

a)



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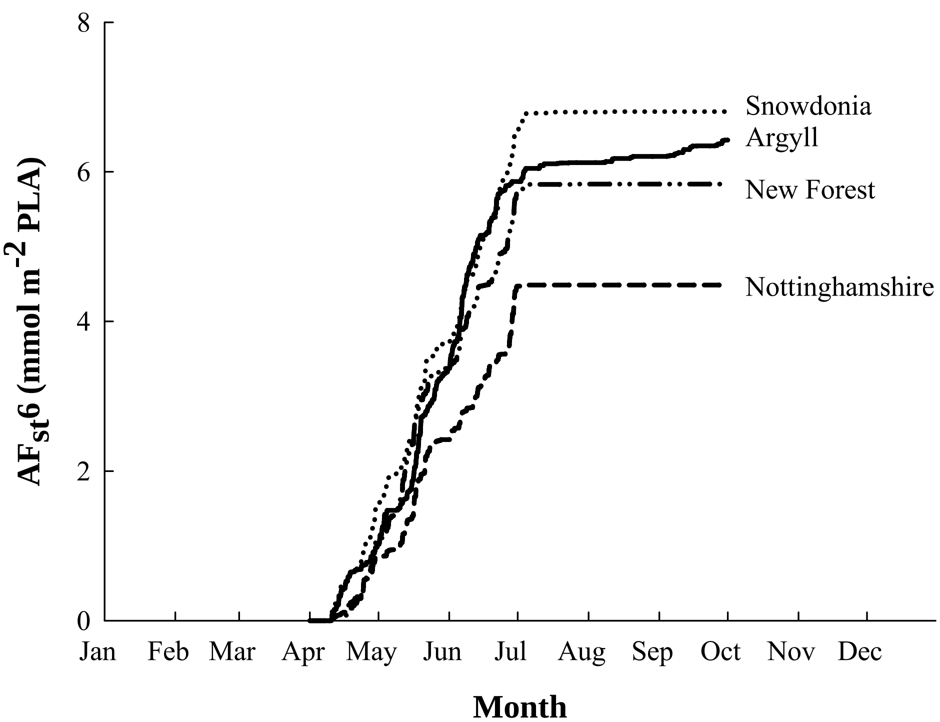


Figure 3.3. a) AOT40 and b) $AF_{st}6$ for grass in selected areas in the UK

4. Changes in Ozone Exposure and Effects of Emission Controls

The analysis described in Section 3 relates to current ozone exposures. It is also based on the current climate, which influences the stomatal conductance and hence the ozone flux to sites of damage in the leaf. However, it is important for assessment of the significance of ozone as a threat to the conservation of key habitats and species in the UK that the significance of current and future changes in ozone exposure are also considered. Both past and future trends of ozone exposure are largely driven by changes in the emissions of ozone precursors. Because of the complex chemistry underlying the formation and destruction of ozone in the atmosphere, the link between emission control and changes in ozone exposures is difficult to predict. Detailed discussion of this is beyond the scope of this report, but it is important to emphasise that it is possible that measures to control emissions of NO_x can have the effect of both reducing ozone concentrations (primarily in remote areas) and increasing ozone concentrations in urban and more polluted areas. This latter effect is because of the rapid reaction of ozone with nitric oxide (NO), which is the main oxide of nitrogen emitted from fuel combustion, e.g. in vehicles and power stations. Thus, in some cases, measures primarily adopted to reduce impacts of nitrogen dioxide (NO_2) on human health may have adverse effects in terms of increasing concentrations of ozone.

4.1 Recent trends in ozone exposure

A number of analyses have been conducted of trends in ozone exposures at different sites in the UK over the last 20 years. Interpretation of the complex trends in ozone concentrations at different sites in the UK, and their dependence on the particular ozone metric which is used to summarise the data, is also beyond the scope of this report, and will be reviewed in much greater detail in the reports of Defra advisory groups, the Air Quality Expert Group (AQEG) and the National Expert Group on Transboundary Air Pollution (NEGTAP). These reports are discussed in more detail in Section 4.3. However, a brief summary of the key factors that influence these trends is important to an understanding of how ozone exposure of different BAP Priority Habitats may have changed over recent decades, and is likely to change in the future.

In effect, there are three major processes influencing these changes at UK and European sites:-

1. *Increases in concentrations* at sites with relatively high NOx concentrations (primarily but not entirely urban and suburban sites) due to the reduced 'titration' of ozone by NO emissions. This effect will primarily influence mean, rather than peak ozone concentrations.
2. *Decreases in concentrations* at rural sites primarily in southern Britain during summer photochemical episodes due to improved control of emissions of ozone precursors, both NOx and VOCs. This effect will primarily influence peak, rather than mean, concentrations in summer episodes that have a European scale.
3. *Increases in concentrations* at remote sites, primarily in northern and western Britain, due to increasing northern hemisphere background ozone concentrations, primarily linked to increased northern hemisphere NOx emissions and inter-continental transport of tropospheric ozone from North America and Asia. This effect will primarily influence mean, rather than peak concentrations.

These complex and competing effects mean that any prediction of future exposures at a specific SSSI or NNR would be very uncertain. However, one consistent trend, which varies in size between sites, is that peak concentrations have tended to decrease over the last two decades, whereas mean concentrations have tended to increase (NEGTAP, 2001).

The most recent comprehensive analysis of data within the UK national monitoring network to support this conclusion has been undertaken by Carslaw (pers. comm) for the forthcoming AQEG report. His analysis included a consideration of trends of annual mean concentrations and peak (99.9%ile) concentrations at 16 rural and remote sites in the UK over the last 20 years. The results are illustrated in Figure 4.1 and 4.2. This analysis does not include the AOT40 index, and hence more detailed assessment of the implications for effects on vegetation must await further analysis, which is expected to be undertaken for the NEGTAP report during 2007 and 2008.

In terms of mean concentrations, the only significant trends found by Carslaw (pers comm.) were for an increase over time. However, Figure 4.1 shows that there is considerable variation between sites – some sites (e.g. Strath Vaich in northern Scotland) show a steady increase over that period, some sites (e.g. Wicken Fen in Cambridgeshire and Sibton on the Suffolk coast) show a rapid increase over the last five years in particular, while some (e.g. Ladybower in the Peak District, Eskdalemuir in southern Scotland, and Lough Nagar in Northern Ireland) show no clear trends. It should be noted that none of the 16 sites is in Wales, so trends in this part of the UK are very uncertain; Aston Hill, close to the English/Welsh border, shows a slight upward trend.

In contrast, almost all sites show a decline in peak concentrations (Figure 4.2), with significant downward trends being found at sites in almost all parts of the country. The only exception is Wicken Fen, which shows a recent increase in peak concentrations.

A similar analysis has been conducted for urban and suburban sites. The results for trends in mean ozone concentrations were similar to those for rural and remote sites, with a mean rate of increase which was similar. However, the pattern for peak concentrations was quite different. No urban or suburban site showed a significant trend; while some sites showed evidence of a decrease in peak concentrations, those at other sites appear to be increasing. Although specific consideration of urban habitats is outside the scope of this report, due to their varied nature, it should be noted that these results suggest that some urban sites of conservation importance may have experienced an increase in both mean and peak ozone concentrations in recent years.

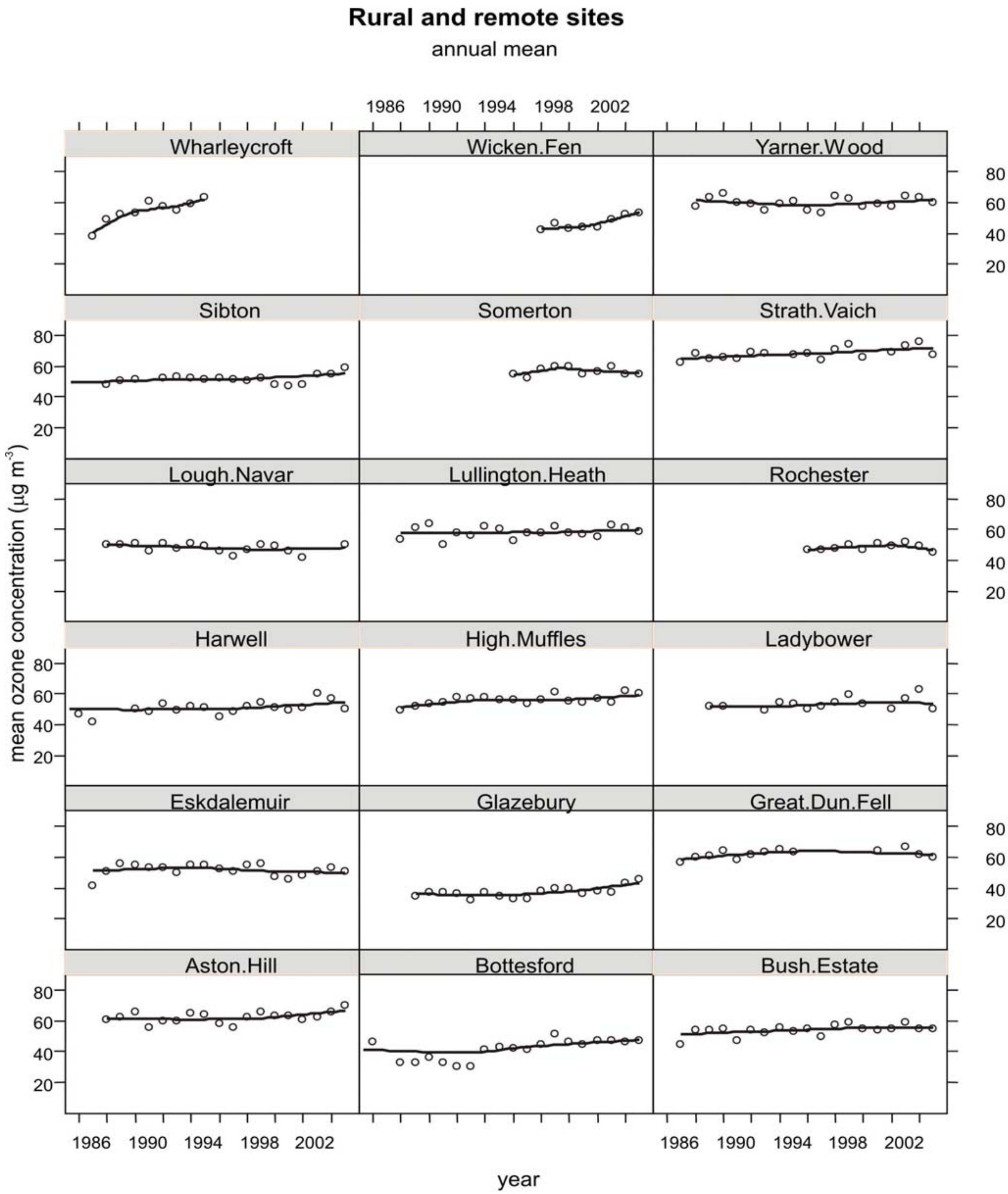


Figure 4.1. Trends in annual mean ozone concentrations at rural and remote sites in the UK national network (Carslaw, pers.comm.)

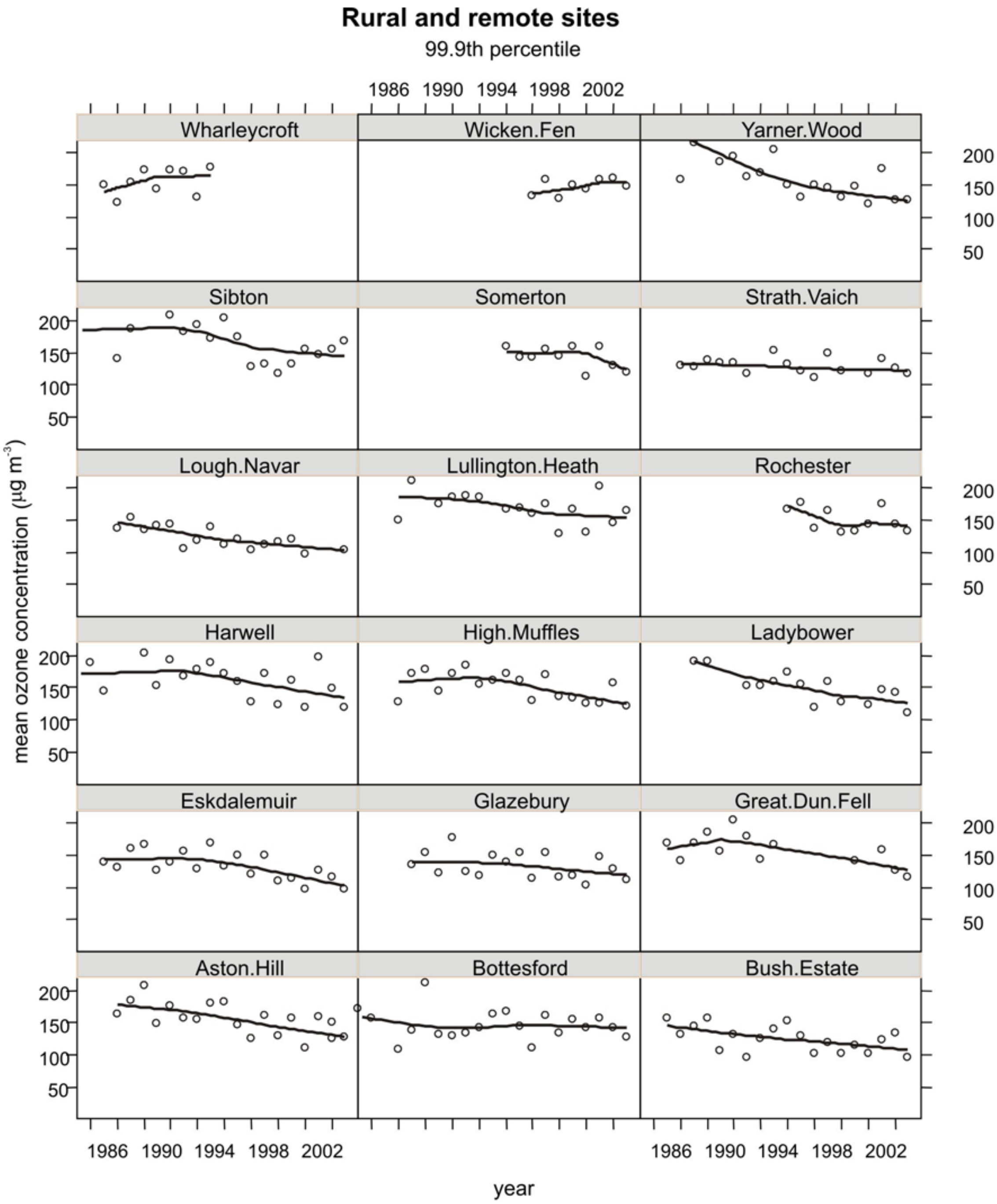


Figure 4.2. Trends in peak (99.9%ile) concentrations at rural and remote sites in the national network (Carslaw, pers.comm.)

4.2. Future trends in ozone exposure

Analyses of future trends in ozone exposure in the UK are complex and reflect the effect of several different processes. A number of different computer models operating over different scales, and of different complexity, have been used to predict these trends. Detailed analysis of these model projections based on different emissions scenarios at a local, European and global scale is well beyond the scope of this report. They will be considered in more detail in the reports of AQEG, NEGTAP and the Royal Society (see Section 4.3).

However, one aspect of significance is that many protected sites are in remote areas where the effects of changes in hemispheric background ozone concentrations may be greater than those of changes in local NOx emissions or the effects of control of regional emissions of ozone precursors in Europe. The implications of the trend of increased hemispheric background concentrations for effects on vegetation were assessed by Ashmore *et al*., (2002) and Coyle *et al.,* (2003), based on trend analysis carried out by CEH Edinburgh. The predicted effects by 2030 were for a considerable increase in AOT40 values, an alteration in seasonal patterns, with higher spring concentrations, and a reduction in the north-south gradient in ozone exposures. This implies an increased risk of ozone impacts on biodiversity especially at more remote northern sites and for groups of species (e.g. woodland bulbs) that are dependent on spring growth.

The interpretation of these results depends rather critically on interpretation of the effect of subtle changes in the frequency distribution of ozone concentrations around 40ppb – a small shift in mean concentrations of 2-5ppb can produce a large increase in AOT40, but there is very little experimental evidence of effects of ozone concentrations of 40-50ppb on any species. This gap is now beginning to be addressed with specific reference to communities of conservation interest within the Defra Terrestrial Umbrella programme, as described in Section 2 of this report. In particular, studies by CEH Bangor are comparing the effects of changes in both mean and peak concentrations, and their combination, and a large-scale experiment in Allendale, Northumberland which is due to start in Spring 2007 will expose an upland grassland community, under management to enhance biodiversity, to increases in mean concentrations.

A second point is that analysis of the implications of these changes might be best considered in terms of changes in flux, rather than AOT40, for two reasons. Firstly the critical flux threshold, and cumulative flux, is much less influenced by the threshold exceedance effect than is AOT40, and hence provides a more robust basis for risk assessment. It is also likely that changes in mean concentration are likely to have a bigger impact on seasonal flux than on AOT40. The second reason is that these changes in ozone exposure will not occur in isolation. The increased in CO_2 concentration, temperature and soil moisture deficit which may also occur over the same period, due to the continued increase in CO_2 emissions and the associated climate change, could lead to decreased, rather than increased flux, if their combined effects outweigh that of increased ozone concentrations. Given that flux based assessments give a different spatial pattern of risk across the UK than AOT40 (see Section 3), more detailed assessment of the likely trends in terms of ozone flux is needed.

What is very uncertain is what these future trends in ozone exposure and flux mean in terms of future impacts on Priority Habitats. Besides the essential experimental work to better determine the implications of changing patterns of ozone exposure, more simulations of past and future trends of both AOT40 and modelled flux are needed for specific locations of high conservation importance

These need to be selected to represent a range of different types of location, from urban sites through to remote montane areas.

4.3. Assessments of Ozone Impacts in a Policy Context

There are three bodies currently examining ozone exposure, impacts and policy in a UK context.

1. Defra's Air Quality Expert Group (AQEG) is currently reviewing ozone exposures in the UK, with a primary focus on urban exposures and implications for effects on human health. However, some of the analysis being conducted by this group will be relevant to rural exposures and impacts. A first consultation draft of this report is expected to be completed during 2007.

2. Defra's National Expert Group on Transboundary Air Pollution (NEGTAP) is likely to be starting a new report following up its influential review of air quality and its impacts on the natural environment in the UK, which was published in 2001. This is likely to be a shorter report focussed on key trends since the late 1990s, and their implications, but will also update the evidence of impacts of nitrogen deposition and ozone. The findings and recommendations of this report are likely to have a significant impact on the policy of the UK Government and the devolved administrations with respect to the impacts of air pollution on protected sites and sensitive habitats. It is likely that the first draft of the report will be produced during 2008.

3. The Royal Society is currently conducting an investigation of ground-level ozone, which will include impacts on the natural environment. This group has called for written evidence, and will also have a day of oral evidence on impacts and discussion in mid-May. The report is due to be completed by the end of 2007. Since the AQEG and NEGTAP reports will focus, in future scenario analysis, on the period up to 2020/2025, the Royal Society study will take a longer-term perspective, over the whole of this century. This will mean that greater weight needs to be given to ozone in the context of climate change, and that a substantial degree of horizon scanning activity will be needed.

If the trends discussed in Section 4.2 above do represent likely scenarios of ozone exposure in the UK over coming decades, it will be clearly important that the implications of different policy options for nature conservation are fully considered in these reports. Impact assessment in both the UK and Europe has historically focussed on effects on human health and crop production, because formal cost-benefit analysis is possible. The importance of obligations by the UK, and other countries, to protect biodiversity under European and international agreements, such as the Habitats Directive and the Convention on Biological Diversity, need to be given greater weight in these assessments, since there is now evidence that current levels of ozone in the UK can have an impact on sensitive communities, and hence may be a threat to nature conservation objectives for these communities in the UK.

4.4. Policy Initiatives and Issues

The assessment of trends in ozone exposures at different sites given above clearly identifies that changes over recent decades, and in the future, are influenced by three separate processes. These are effectively equivalent to three different policy arenas:-

1. Local urban air quality management. The key focus here is the National Air Quality Strategy (NAQS), revisions to which are currently being finalised following a consultation period. This strategy is primarily linked to benefits for human health in urban and suburban environments and specific air quality objectives set to minimise effects of human health. Baseline modelling for the NAQS focussed on ozone metrics relevant to health effects, and did not include AOT40 values, or other indicators of effects on vegetation. However, the modelling clearly identified the likelihood that ozone concentrations are likely to have increased by 2020 at rural and urban sites, due to the combined effect of reduced NOx emissions on local concentrations and the rising hemispheric background concentration. A similar conclusion was reached in analysis for the European Commission's Clean Air for Europe (CAFE) programme in which the UK was the only EU25 country for which currently planned emission reductions for NOx would not prevent an increase in ozone exposures. Policy interventions assessed for the UK in the revision of NAQS focussed on NOx control and not VOC control, primarily because the latter was considered be less cost-effective.

2. European air quality management. There are major processes underway which will influence future emission control for ozone in Europe. The first of these is the Gothenburg Protocol Review process, which is being carried out within the Convention on Long-Range Transboundary Air Pollution (CLRTAP). The results of these reviews will be reported to the Executive Body of CLRTAP in December 2007, after which negotiations on revision of the Protocol may follow. The scientific assessments under the review process include impacts on vegetation, and the effects of using critical levels based on flux rather than AOT40. However, if a flux-based approach is adopted, this may minimise consideration of ozone effects on semi-natural communities, for which the critical level is still based on the AOT40 concept.

The second process, which is proceeding in parallel, is revision by the European Commission of the National Emissions Ceiling (NEC) Directive, for which an initial proposal is due during 2007. Given the enlargement of the EU, it seems unlikely that revision of national emissions targets under the Gothenburg Protocol could proceed until the NEC process was completed. The assessment of impacts of different emission control options was carried out by IIASA under the CAFE programme. However, this process does not use the same environmental targets as the critical levels agreed within CLRTAP, as only AOT40 was used to assess the benefits of different emission control strategies.

These results of the CAFÉ process should be considered in the context of the targets for ozone in the 3rd Air Quality daughter directive. These set two types of targets for ozone: target values to avoid harmful effects, to be attained where possible by 2010, and long-term objectives, below which direct adverse effects are unlikely, and for which Member States need to implement cost-effective and proportionate measures. There is no specific date for meeting long-term objectives, although reviews of progress are based on a benchmark of 2020. The values for vegetation (converted from the official units of $\mu g\ m^{-3}$. h) are a target value of AOT40 of 9000 ppb.h averaged over five years, based on a three-month period (May-July), and a long-term objective of 3000 ppb.h over the same period. The evidence summarised in this report provides clear evidence of harmful effects on sensitive positive indicator plant species occurring above the target value; however, it is unlikely that the target value (three month AOT40 of 9000 ppb.h), based on a five-year average, is exceeded in the UK (NEGTAP, 2001). The long-term objective was set to be consistent with the critical level for adverse effects on crop yields at that time; for proper evaluation of effects on semi-natural vegetation, it would need to be modified to the 6-month AOT40 value of 5000 ppb.h.

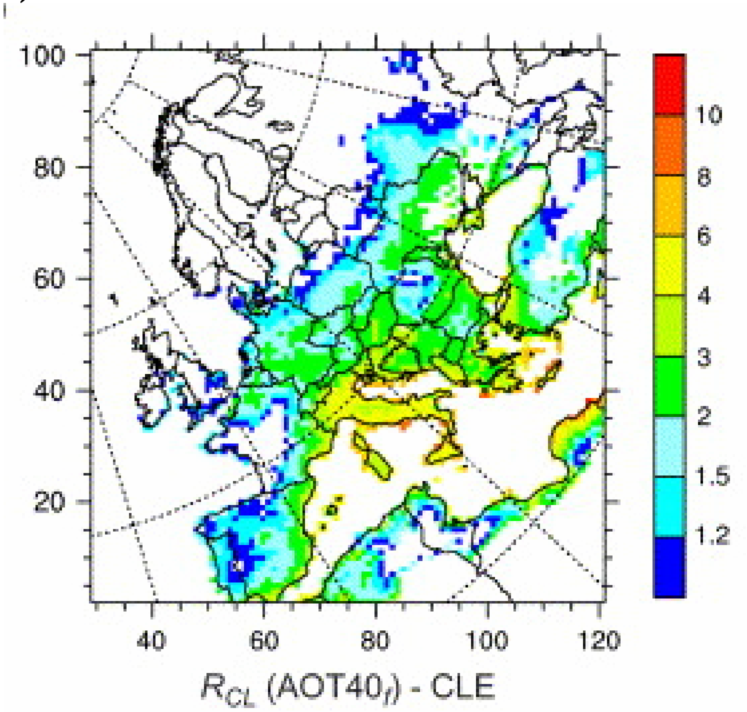
Hence, the critical issue for future EU policy on emission control is the cost-effectiveness of measures to reduce ozone exposures towards or below the long-term objectives. The CAFÉ programme used integrated assessment modelling to support the development of the European Commission's new Thematic Strategy for Air Quality. This process effectively uses a cost-benefit analysis to develop an optimal emission control strategy, but considers all emissions and all effects. Since the health effects of particulate matter were the dominant effect, optimisations that reduced these urban effects were favoured over policies that reduced ozone concentrations, as well as acidification and eutrophication. For rural UK sites, both NO_x and VOC control alone were modelled to improve air quality relative to the baseline scenario in 2020 which increased ozone levels. However, to achieve reductions compared with 2003 levels, reductions in emissions of both NOx and VOCs of about 60% by 2020 in both the UK and continental Europe would be needed, because of the trend of increasing northern hemisphere concentrations. Hence, it is clear that that reducing ozone exposure in rural Britain will not be simple – indeed, assuming no control of northern hemispheric background emissions and a continuing trend of increased background concentrations, major emissions control would be needed, simply to prevent increases in ozone concentrations. These measures were not identified as the most cost-effective within the CAFÉ analysis.

The effects of basing an assessment of the benefits of emission control policies based on the AOT40 index or a flux index are illustrated in Figure 4.3. This analysis was conducted by Simpson *et al.,* (2007) for forests, using a generic flux model parameterisation, and the EMEP photochemical model. The results for 2020 are for a Current Legislation (CLE) scenario which considers the effects of policies on emission control which have already been agreed in Europe, including future emission controls. They can be compared with the current situation which is shown in Figure 3.1. The plotted values are the ratio of the modelled AOT40 or flux to the corresponding critical level – a value below 1 indicates that the critical level is not exceeded.

It is important to note, when interpreting Figure 4.3, that the analysis does not take account of changing climate – it uses the same climatic data as the baseline – and does not take account of the effects of either local NOx emissions, due to the scale of the model, or changes in northern hemisphere background concentrations due to emissions outside Europe. The results clearly show, when compared to Figure 3.1, that these planned emission controls have a significant effect on the area of the UK which is in exceedance of a critical level based on AOT40, but a much smaller impact for a critical level based on flux.

Within the analysis that has been conducted for CLRTAP on ozone, there is an important difference between how ozone exposure and effects are considered for crops and forests, and for semi-natural vegetation. While flux-based critical levels have been developed and accepted for risk assessment for crops and forests, the critical level for semi-natural vegetation remains based on the AOT40 concept. This clearly creates some concerns about the weight that will be given to effects on semi-natural vegetation in assessments conducted under the review of the Gothenburg Protocol. Nevertheless, this may not be a concern in terms of minimising the risk to key conservation objectives in the UK. Since the use of flux rather than AOT40 generally leads to a distribution of risk which is more evenly distributed across Europe, instead of showing a strong north-south gradient, use of flux is likely to lead to lead an optimisation of emission controls which gives equal weight to protecting northern and southern Europe. In contrast, an over-emphasis in meeting AOT40-based critical levels in order to protect semi-natural ecosystems could, paradoxically, lead to reduced protection of sensitive habitats in the UK.

a)



b)

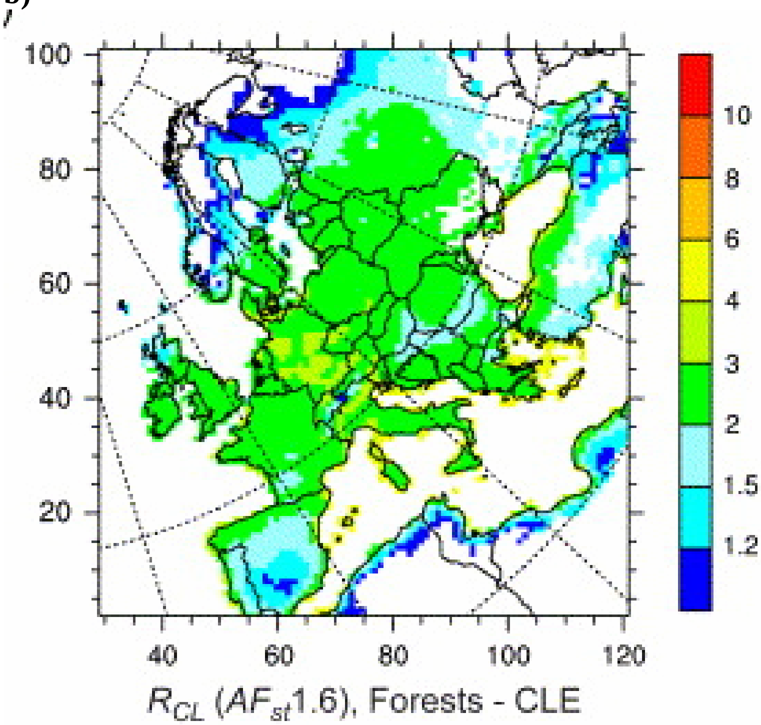


Figure 4.3. Exceedance of critical levels for forests across Europe in 2020, based on planned emissions controls using (a) AOT40-based critical levels and (b) flux-based critical levels. From Simpson *et al.*, (2007)

3. Hemispheric background concentrations. There is no obvious policy forum within which the global scale trends in ozone concentrations can be assessed and debated. The scenarios for changes in northern hemispheric background concentrations that have been used are closely linked to emissions projections which are derived from the same basic scenarios of population growth, transport, agricultural production, energy consumption, etc. as those used within the Inter-Governmental Panel on Climate Change (IPCC) to predict future concentrations of CO_2 and other radioactively active gases. However, IPCC does not consider impacts of ozone directly, only its indirect effects as a greenhouse gas.

Due to the recognition of the importance of increasing northern hemispheric background concentrations in influencing ozone exposures in Europe, CLRTAP has established a Task Force on Hemispheric Air Pollution. This Task Force is due to report in 2009, but will also provide an interim report for the Gothenburg Protocol Review process, at the end of 2007 The Global Atmospheric Pollution Forum (GAP Forum) is a separate independent initiative on global air pollution issues, originated by the International Union of Air Pollution Control Associations (IUAPA). It aims to bring together different regional experts to assess how air pollution can most effectively be managed; the GAP Forum is also considering this issue of northern hemispheric background ozone. These activities will provide a first assessment of the issue, and the basis for further discussion of policy measures.

All assessments of the future impacts of ozone whether at local, European or global scales, need to consider the implications of climate change. The effects of climate change in the UK on air quality are considered in some detail by AQEG (2007), while the effects on impacts are likely to be considered in more detail in the NEGTAP report. A key issue is that an increased frequency of hotter drier summers will lead to an increase in summer episode ozone concentrations, but that flux and deposition in such summers may be reduced.

In summary, effects of different emission control policies in reducing the impacts of ozone on BAP Priority Habitats in the UK will not be a major policy driver in isolation. This is consistent with the limited evidence of major effects of current ozone exposures in the UK which is revealed in this report, although this partly reflects a lack of scientific work. The major driver of policy assessment and implementation in the next five years will be effects on human health. However, it is important to ensure that the implications of different policy options for ozone exposures and potential effects on statutory biodiversity objectives are properly considered, in particular because of the possibility that ozone exposures at some sensitive sites may increase over the next 2-3 decades as a result of local NOx control, trends in northern hemisphere background concentrations, and the likelihood of warmer summers.

4.5. Importance of VOC Emission Control

There are four major precursors of ozone. Two of these are the long-lived species carbon monoxide (CO) and methane (CH_4) for which emission control will mainly affect global background concentrations. Since methane has a short atmospheric lifetime, and has other important effects on global climate, measures to reduce global methane emissions may be a relatively cost-effective approach to reducing ozone concentrations over the next two decades. The other two precursors are relatively short-lived species, nitrogen oxides (NOx) and volatile organic compounds (VOCs). It is control of these species that is most important for national and European policy; these are closely inter-linked, both because of the regulatory framework, but also because models consistently demonstrate that UK emission reductions in the absence of similar reductions across Europe, have little benefit in terms of UK ozone levels.

Modelling of the benefits of emission control policy for the review of the National Air Quality Strategy was undertaken using the Ozone Source-Receptor Model (OSRM) by Hayman *et al.,* (2006). The results highlight that:-

- Reductions in NOx emissions alone can cause both increases and decreases in ozone exposure, depending on the site and the ozone exposure index used
- In contrast, VOC emission reductions alone always reduce ozone concentrations
- Combined reductions in NOx and VOC emissions are always more effective than reducing NOx emissions alone
- UK and European actions are always much more effective than UK action alone

Given these findings, it would appear that VOC emissions should be a major focus of policy to reduce ozone concentrations, but these measures were not identified as cost-effective in CAFÉ. There are a number of reasons for this, including the fact that measures to reduce VOC emissions had little benefit, apart from those for ozone, in terms of the effects on human health, which were the main driver of the benefits of the different strategies.

A further factor is that the models used in the CAFÉ analyses simply consider overall VOC emission reductions. This ignores the important fact that VOCs cover a large range of individual compounds, which differ greatly in their reactivity and contribution to ozone formation. Derwent *et al.,* (2007) have demonstrated that targeted control policies focussed on replacement of reactive groups of VOCs by those of lower reactivity may be a more effective (and more cost-effective) approach than overall mass-based emission control. Derwent *et al*., (2007) point out that the benefits of VOC control to date for ozone concentrations have largely derived from measures to reduce evaporative and exhaust emissions from motor vehicles. However, Hayman *et al.,* (2006), in their analysis of effects on UK ozone concentrations, which included consideration of VOC reactivity, identified that further improvements in ozone concentrations over the period 2010-2020 should focus on stationary sources, and especially those from the chemical, oil and gas sector, and manufacturing industries that use solvents.

In this context, it is also relevant to note that emissions of VOCs from natural sources (biogenic VOCs) may be significant precursors of ozone formation. The most important of these are reactive hydrocarbons such as terpenes, whose emissions increase rapidly with temperature. Across the UK, Sitka spruce is the most significant source of terpene emissions, because of its high emissions and large area, although it is not generally grown in areas where there is greatest photochemical ozone formation (Stewart *et al*., 2003). Emission rates vary significantly between tree species; for example, oaks, willows and poplars have relatively high emissions fates, while maples, birches and pines have relatively low emission rates (Donovan *et al*., 2005). Thus future forest planting policy may need to consider the implications of choice of tree species for biogenic VOC emissions, alongside other factors (AQEG, 2007).

5. Conclusions

At present there is relatively little information available for use in assessing the sensitivity of different plant communities to ozone, and whether the impacts of ozone will be detrimental to BAP objectives for different habitats. Grassland communities are the best studied, although information is not always clear cut. For example, there are large predicted variations in the sensitivity of NVC communities within lowland calcareous grasslands. There is some evidence for grassland communities that the effects of ozone could make it more difficult to achieve specific conservation objectives. Whilst tree species are relatively well studied, there have been almost no studies on the effect of ozone on woodland ground flora. It is possible, for example, that decreased growth of trees leading to more open woodland canopy species may actually be beneficial to some woodland ground flora. However, no studies addressing this issue have been carried out. There are very few studies of community responses to ozone in other habitats, such as wetlands, heath, montane and inland rock habitats.

It is likely that the long-term effects of ozone on these communities in terms of BAP objectives will depend on the sensitivity of positive indicator species (and negative indicator species which have not been considered in this report) and on the response of dominant species. Thus, potentially an assessment of community sensitivity could be developed from knowledge of the response of individual species. However, this is more problematic than for effects of nitrogen deposition and acidification for which species habitat preferences can be used to predict response. The only major factor identified in the OZOVEG database of 83 species as being strongly associated with ozone sensitivity is membership of particular families, especially the *Fabiaceae* (Hayes *et al*., 2007), and this suggests that Priority Habitats with a high proportion of legumes might be at greatest risk. Therefore, the only useful approach is an empirical one, in which a targeted strategy is used to expand this database and its relevance to key species for BAP Priority Habitats. The predictive models of the likely sensitivity of communities to ozone based on Ellenberg Indicator values (CORI) or meta-analyses of individual species sensitivity to ozone, are often based on studies performed outside the UK, or use relatively small sample sizes, and should not be treated as definitive at this stage. While these models provide an important conceptual basis for risk assessment, a stronger evidence base, including a greater range of species, is needed if they are to be applied effectively There is, therefore, a need for UK based experimental studies on both individual species and communities, investigating the effects of both increasing background and peak ozone concentrations. There are currently no data on ozone threats to BAP Priority Species. Therefore a more detailed analysis of Priority Species distribution in relation to ozone concentrations and their habitat requirements is recommended. In summary, this report has presented a framework for assessment of community sensitivity based on the existing data, and the analytical framework for species and community sensitivity developed at CEH Bangor. However, this will remain of limited predictive value without significantly more experimental data.

In England, most BAP Priority Habitats are exposed to AOT40 values in excess of critical levels, with the majority of these areas occurring in the south-east of the country. Those Priority Habitats with a southerly distribution, such as Lowland calcareous grassland, have the highest overall exposure. In Scotland, upland habitats are exposed to the highest ozone exposures, with Native pine woodlands, Upland oakwood and Upland calcareous grassland having the highest proportion of habitat in high AOT40 areas. Similarly, the highest levels of ozone exposure in Wales occur in upland areas, with Blanket bog having the highest AOT40 exposure. As in England, but unlike Scotland and Northern Ireland, most Priority Habitats in Wales are exposed to AOT40 values in excess of the critical level. The BAP habitat ozone exposure data presented here is an initial assessment of likely exposure in Britain. A more detailed, GIS based analysis of the exposure of habitats to ozone would be beneficial in identifying habitats most at risk and, subsequently, research priorities.

The flux method of assessing ozone risk is considered to be superior to AOT40 based approaches, which do not take account of climatic and seasonal influences on plant uptake of ozone and rely solely on atmospheric concentrations. This report demonstrates that use of the former can lead to radically different outcomes when compared to the latter. Whilst AOT40 based risk assessments showed significantly higher ozone exposure in the two English squares than those in Scotland and Wales, modelled flux data for productive grasslands suggest that the opposite is the case, giving AFstY values in Snowdonia and Argyll that are larger than those for the two English squares. It is possible, therefore that a UK wide flux-based assessment of ozone risk would lead to a substantially different assessment of Priority Habitats at greatest risk than an AOT40 approach. We stress that any such assessment would require considerable work on species and community specific parameterisation of the flux model.

There are major trends in ozone concentrations in the UK which will significantly change the patterns of ozone exposure. In urban and suburban areas, which have not been considered in this report in terms of habitat sensitivity, an increase in mean concentrations with a limited decrease in peak concentrations, may occur primarily because of local control of NOx emissions. In rural areas of southern Britain that are most influenced by photochemical episodes, peak concentrations may be reduced, but this may be partly offset by the effects of reduced NOx emissions and an increasing northern hemispheric background concentration. Finally in more remote northern and western areas of Britain, there will be less influence of local or European emissions control, with trends in northern hemisphere background concentrations being the dominant factor. Overall, it is likely that mean, but not peak, ozone concentrations will increase over the next 30 years with higher spring concentrations and a reduction in the north-south gradient in ozone exposures. It is, however, impossible to predict with the current knowledge base how these changes will affect BAP habitats.

Currently the Defra groups AQEG and NEGTAP, and the Royal Society, are examining ozone exposure and policy issues in the UK with reports expected in late 2007 and 2008. At the same time, discussion of new policy measures within EU and CLRTAP, which will influence future ozone exposures significantly, will be underway. If ozone trends discussed in this report represent likely scenarios of ozone exposure, it is important that the implications for different policy options for achievement of BAP objectives in the UK are fully considered in these discussions.

6. Recommendations

The following key recommendations are identified:

- Little or no research to date has focussed on Priority Species, or rare and endangered species. An assessment of the risk to such species would be useful. A more detailed analysis of Priority Species distribution in relation to ozone concentrations and their habitat requirements is recommended.

- There are a number of habitats with high ozone exposure, and which contain sensitive species, for which no experiments on community level effects of ozone have been carried out. There is a need for experimental investigation of the ozone sensitivity of poorly studied Priority Habitats.

- The vast majority of ozone research in woodlands has focused on tree species and there are very little data on impacts the under-storey. Community level fumigations of woodland communities are needed to evaluate ozone impacts on ground flora.

- While some studies have been conducted of community response of grasslands to ozone, more focussed experiments on specific communities are needed. Attention needs also to be focussed on the effects of ozone on management measures to enhance or restore the condition of specific sites.

- More experimental studies are needed that specifically address effects of the changing patterns of ozone exposure in the UK.

- Predictions of community ozone sensitivity are often based on studies of relatively small numbers of species. There is a need to increase the value of the existing databases and models to predict species and community sensitivity, by experimental studies that target positive and negative indicator species for key Priority Habitats.

- The BAP Priority Habitat ozone exposure analysis presented in this report is an initial assessment of their relative exposure to ozone. A more comprehensive GIS-based analysis is needed to provide an accurate measure of relative risk from ozone exposure in England, Scotland, Wales and Northern Ireland.

- The limited flux-based analysis presented in this report clearly shows that the relative risk of ozone impacts in a region from absorbed dose of ozone can differ substantially from those predicted by atmospheric concentration alone. It would be very valuable to develop and parameterise flux models that could be applied to BAP Priority Habitats and Species at high risk of ozone impacts.

- It is important that effects of ozone exposures on nature conservation are given more weight in assessments of EU and UK assessment of policies to reduce emissions of ozone precursors. Measures to reduce ozone precursors in the UK alone are likely to have little benefit, while policies that focus on emissions of VOCs with high reactivities are likely to be most effective.

- The work of the Royal Society working group and AQEG during 2007 and NEGTAP during 2007 and 2008 will be important in influencing future thinking on ozone impacts and policy. It is important that JNCC actively engages with these reports to ensure that their analysis takes due account of conservation policy objectives for the UK.

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