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THE EFFECTS OF OZONE ON NATURAL VEGETATION INCLUDING REQUIREMENTS FOR LEVEL II MODELLING AND MAPPING

Technical report by the Coordinating Centre of the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation)

Introduction

1. One of the aims of ICP Vegetation is to map natural vegetation species and communities which are "at risk" from ozone pollution in Europe by identifying areas where these species and communities coincide with high levels of ozone.

2. Ozone injury has been observed on natural vegetation in Europe in ambient air conditions (Becker *et al.*, 1989) and biomass reductions have been recorded in unfiltered compared to filtered air (Fuhrer *et al.*, 1994; Evans and Ashmore, 1992; Pleijel *et al.*, 1996). Obtaining reliable experimental data on which to base critical levels for natural vegetation species is thus an

increasing priority. Unfortunately, it is not as easy to decide on the criteria for assessing the sensitivity of natural vegetation to ozone as it is for crop responses. Seed output is a possible effect-criterion for annuals and biennials, but may not be appropriate for perennial plants. In practice, visible injury and growth in ozone compared to control conditions are usually used. The implications of effects of ozone pollution on community structure and functioning have still to be determined.

2. This report considers the evidence for impacts of ozone on species of semi-natural and natural vegetation (for the purpose of this report, both semi-natural and natural vegetation will be classed as "natural" vegetation). The current critical levels and requirements for level II modelling and mapping are also discussed and the ICP Vegetation research on ozone effects on natural vegetation is described.

I. THE EFFECTS OF OZONE ON NATURAL VEGETATION

3. Ozone injury is less specific and less easy to identify on natural vegetation than on crops, as the symptoms range from stippling or chlorotic flecks to non-specific reddening of the leaves (a general stress response in plants). Reports of visible injury after ambient ozone episodes or short-term artificial exposures of up to 100 parts per billion (ppb) have been noted on over 50 species (for details, see the 2001 Annual Report of ICP Vegetation (Mills *et al.*, 2001)). For example, Nebel and Fuhrer (1994) assessed the sensitivity of 31 native species in Switzerland. They classified 6 species as sensitive (visible injury symptoms appeared after 6 days of exposure to 100 ppb), 15 species as intermediate (injury occurred after an additional 3-day exposure to 150 ppb) and 10 species as resistant (no visible injury). In a longer-term study, Bergmann *et al*. (1996) recorded visible injury on 11 out of 16 natural vegetation species exposed to 70 ppb for 7h d^{-1} in open-top chambers.

4. Some species may show biomass reductions due to ozone at near ambient levels. For example, 18 out of 27 species investigated in Sweden had increased growth in filtered air compared to non-filtered air with added ozone (Pleijel and Danielsson, 1997). In experiments conducted in Germany, some species, e.g. black nightshade (*Solanum nigrum*), common mallow (*Malva sylvestris*) and groundsel (*Senecio vulgaris*), had a loss of leaf biomass of more than 30% with 70 ppb ozone treatment within about six weeks, whereas fat hen (*Chenopodium album*) and common nettle (*Urtica dioica*) showed no changes in biomass or any other parameter measured (Bergmann *et al.*, 1996).

5. In the presence of ozone, some species, such as sheep's fescue (*Festuca ovina*), preferentially partitioned biomass to shoots rather than to roots, which may give the plants a competitive disadvantage when they are in species mixtures, even though there appears to be no significant effect (on a total weight basis) when the plants are grown singly (Cooley and Manning, 1987, Franzaring *et al.*, 2000). As a plant matures, flowers and develops seeds, these sinks receive a relatively high proportion of the available assimilate. Ozone exposure during this time can influence the biomass partitioning to these sinks. For example, long-headed poppy (*Papaver dubium*) and hare's-foot trefoil (*Trifolium arvense*) showed reduced shoot biomass and increased seed/flowering allocation, whereas fat hen (*Chenopodium album*) and pineapple weed *(Matricaria*

discoidea) showed greater vegetative shoot weight and reduced reproductive allocation (Bergmann *et al.*, 1995).

II. THE ECOLOGICAL IMPLICATIONS OF EFFECTS ON NATURAL VEGETATION

6. While individual plant responses to ozone are important, the effects of ozone on plant communities have been highlighted as being even more important when establishing critical levels. This is an area where much further work is needed as it is not always possible to extrapolate from single species studies to ecosystem responses. Thus, the effects of ozone on real or artificial communities need to be studied directly.

7. Differences in sensitivity to ozone may result in the selection of more tolerant species. This could influence the species composition of natural communities and could potentially eliminate the most sensitive species from an ecosystem. Furthermore, air turbulence could also provide different ozone concentrations to different species, as plants growing low in the canopy could experience very different concentrations to those more exposed at the top.

8. In artificial communities, ozone exposure caused a decrease in the proportion of forbs and an increase in the proportion of grasses (Ainsworth *et al.*, 1994; Ashmore *et al.*, 1995; Ashmore *et al.*, 1996), which was consistent with the difference in ozone sensitivity when the plants were grown individually. However, in another study the reverse effect was found (Evans and Ashmore, 1992). In this particular community, it was thought that the low-growing forb species were sensitive to changes in light penetration through the grass canopy due to the ozone-induced changes in growth of the grass species.

9. Effects on individual species can be modified by competition. For example, monocultures and mixtures of crimson clover (*Trifolium incarnatum*) and annual ryegrass (*Lolium multiflorum*) were grown in filtered air and two ozone concentrations for six weeks (Bennett and Runeckles, 1977). The yield and leaf area of ryegrass in mixtures was less affected by ozone than the crimson clover. Although the proportion of ryegrass was greater, at 90 ppb the total dry weight, yield, leaf area, leaf area ratio and tiller number were less depressed by ozone in species mixtures than in monocultures.

10. Davison and Barnes (1998) have suggested that the classification of natural vegetation species as sensitive or resistant could be misleading due to intraspecific variation in response to ozone such as that found in greater plantain (*Plantago major*), alpine cat's tail (*Phleum alpinum*) and white clover (*Trifolium repens*). Species may evolve ozone resistance, which has implications for both community dynamics and the derivation of critical levels. For resistance to ozone to occur, there must be a large reduction in ecological fitness so that there is a selection pressure for evolution. Reiling and Davison (1992a) showed that the relative resistance of greater plantain (*Plantago major*) could be related to the ozone exposure index of the collection site and to some of the climatic variables of the site, particularly the amount of summer sunshine. At present, the evidence suggests that ozone has led to the evolution of resistance in *Plantago major* in the southern half of the United Kingdom.

III. CRITICAL LEVELS FOR NATURAL VEGETATION

11. Critical levels for natural vegetation species were reconsidered at the Critical Levels for Ozone Workshop - Level II (Gerzensee, Switzerland, April 1999, Fuhrer and Achermann, 1999). The following recommendations were made for (level I) critical levels:

(a) For **annuals,** an AOT40 value of 3000 ppb.h, calculated for daylight hours over three months. The critical level for annuals is the same as for crops (wheat), as the response parameter with the highest ecological significance for these plants with a short life cycle is seed output;

(b) For **perennials,** an AOT40 value of 7000 ppb.h over six months (provisionally). Shoot and root biomass have the greatest ecological significance for long-lived species and sensitive herbaceous perennials, e.g. *Trifolium repens* show a 10% reduction in shoot biomass at this level.

(**AOT40** is the sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each hour that the concentration exceeds 40 ppb, accumulated during daylight hours (when the clear sky radiation is greater than 50 Wm^{-2}). Units: ppb.h or ppm.h.)

In both cases, the time period for calculation of the AOT40 is flexible, to relate to the times when the vegetation is most active. No specific critical level for **biennial** species has so far been identified.

12. The most important factors modifying the response to ozone (level II factors) are thought to be: soil moisture and nutrient status; community dynamics and structure; species and genotype; mycorrhizal interactions; deposition of nitrogen; phenology; atmospheric conductivity; vapour pressure deficit (VPD) and air temperature; susceptibility to herbivores and plant diseases; and co-occurrence of other air pollutants.

13. Vapour pressure deficit and soil moisture deficit (SMD) were included in the list because both can modify the response of natural vegetation to ozone via effects on stomatal aperture. However, the degree of response, and therefore protection, is species-specific and may be influenced by the degree of competition, making generalizations difficult (Bungener *et al.*, 1999a, Nussbaum *et al.*, 2000). Nutrient status is undoubtedly an important factor influencing the responses of natural vegetation communities to ozone. So far, very few studies have been performed on this subject. However, Whitfield *et al.* (1998) showed that the effect of ozone on *Plantago major* was greater in root-restricted, nutrient-deficient plants than in unrestricted plants.

14. Semi-natural grasslands are often maintained by management such as cutting or grazing. Ashmore and Ainsworth (1995) showed that the cutting regime had a greater influence on the percentage of the two forbs (white clover (*Trifolium repens*) and germander speedwell (*Veronica chamaedrys*)) than even the highest ozone concentration. The cutting or grazing regime would therefore be an important modifier of the response of these managed communities to ozone.

IV. ONGOING ICP VEGETATION CONTRIBUTIONS TO THE DERIVATION AND MAPPING OF EXCEEDANCE OF CRITICAL LEVELS OF OZONE FOR NATURAL VEGETATION

15. The Coordination Centre has taken on the role of collating international sources of data on natural vegetation with the aim of producing a database of European species “at risk” from the pollutant. Methods for mapping the distribution of ozone-sensitive plant communities are also being investigated.

16. The database is being developed from information published in the scientific literature, together with unpublished information from exposure experiments being conducted by ICP Vegetation participants. In addition to ozone-response information, the database also contains information on botanical characteristics (e.g. leaf shape), phenology (e.g. timing of growth stages), nutrient, soil and climatic requirements, growth strategy, and stomatal conductance. Only data from long-term, field-based exposure systems are included in the database.

17. The natural vegetation database will be expanded in the next two years as new data become available from other sources. The most important of these will be the “Biodiversity in herbaceous semi-natural ecosystems under stress by global change components” (BIOSTRESS) project (led by Mr. A. Fangmeier, University of Hohenhein, Germany). The three-year project (2000-2002) is funded under Key Action “Global Change, Climate and Biodiversity” of the Fifth Framework Programme of the European Commission. It addresses the more subtle effects of ozone on species composition in plant communities, the effects at the ecosystem level and, thus, the possible role of tropospheric ozone for biodiversity and for ecosystem functioning. It involves eight research institutions from six European countries and one closely linked group from the United States. At the end of the BIOSTRESS project, users within ICP Vegetation will be provided with an expert system tool that can predict potential impacts of ozone on vegetation for various ozone scenarios.

18. BIOSTRESS involves a combination of modelling and experimental work under one theoretical framework based on the ecological theory of plant community growth and plant functional types and their interactions. Two types of models are being used: a short-term, mechanistic plant community growth model, and a cellular automaton, functional-type based model suitable for long-term simulations. These models are being used to run virtual experiments with different ozone scenarios. To validate and calibrate the models, data are provided from experiments involving model plant communities which are grown under various ozone concentrations in open-top field chambers (mesocosms) or complex field communities exposed to ozone in chamber-less field exposure systems (complex communities).

19. Six of the eight European institutions involved in the BIOSTRESS project are contributors to ICP Vegetation. A final work package of the project is dedicated to the development of critical levels of ozone for semi-natural vegetation. Data from the project and data from ICP Vegetation activities will be merged in a common database for deriving critical levels. Moreover, the annual meetings of the Task Force on ICP Vegetation contain a separate session on the BIOSTRESS project, and the chairperson and steering committee of ICP Vegetation are invited to participate in the user sessions of the BIOSTRESS consortium meetings. Further information on the BIOSTRESS project can be found at http://www.uni-giessen.de/biostress.

20. ICP Vegetation will also benefit from the use of data from nationally-funded ozone-effects experiments in the United Kingdom, the Netherlands, Switzerland, Slovenia and Spain.

21. Data from all of these sources are being used to identify the species most at risk from ozone pollution, and to derive appropriate critical levels for different types of natural vegetation. ICP Vegetation will also study the possibility of characterizing ozone-sensitive plant communities according to the EUNIS Habitat classification (http://mrw.wallonie.be/dgrne/sibw/EUNIS). This classification is currently being considered by ICP Mapping for use as a framework for mapping vegetation types affected by nutrient nitrogen.

22. Having identified new critical levels for ozone effects on natural vegetation, the next challenge will be to map the areas where exceedance coincides with the location of ozone-sensitive plant communities. Existing maps, such as the Stockholm Environment Institute (SEI) land-cover map, differentiate between improved and unimproved grasslands categorized as dry or wet and according to soil pH. Once plant communities that are considered to be ozone-sensitive have been identified, information on their altitude, climatic, soil moisture and pH requirements will be used (by Ms. L. Emberson, SEI, York; and Mr. M. Ashmore, University of Bradford, United Kingdom) to map their "potential" location within the UN/ECE region. Other sources of mapping information on the location of plant communities are also being investigated, and the maps will be developed in collaboration with the Coordination Center for Effects.

V. FUTURE WORK

23. The results of the ongoing work described above should make it possible to suggest revised critical levels for natural vegetation species at the next Critical Levels for Ozone Workshop, provisionally planned for the autumn of 2002. These may be concentration-based (e.g. in terms of AOT40) rather than flux-based, as research on flux-effect relationships for these species is, because of the complexity of natural vegetation communities, lagging behind that for crops and forest trees. Nevertheless, information will be available on important level II factors such as inter- and intra-species differences in response to ozone, and on the influence of competition. Such information will allow more robust definitions to be made for the critical levels for natural vegetation. The further development of procedures for mapping plant communities at risk from ozone will continue over the next two years, leading to the production of exceedance maps for natural vegetation in 2003.

24. It is also anticipated that a biomonitoring system for natural vegetation using either ozone-sensitive and ozone-resistant biotypes, or species, will be incorporated into the ICP Vegetation experimental programme in the near future. A pilot study with the ozone-sensitive species *Cirsium arvense* (creeping thistle) is taking place this summer (2001) in eight participating countries. Once the method is established, an experimental protocol, including the measurement of stomatal conductance, will be implemented. This experiment will then provide data for the development of a flux-effect model for one species of natural vegetation growing in ambient air that incorporates the influence of level II factors.

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