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RECENT RESULTS AND UPDATING OF SCIENTIFIC AND TECHNICAL KNOWLEDGE

EVIDENCE OF WIDESPREAD OZONE DAMAGE TO VEGETATION IN EUROPE (1990–2006)

Report by the Programme Centre of the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops

INTRODUCTION

1. The Programme Coordination Centre for the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) has collated, to the extent possible, all of the published and unpublished evidence of ozone damage to crops and (semi-) natural vegetation growing in ambient air in European countries over the period 1990–2006 (Hayes et al. 2007). The data have been analysed in relation to maps of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), which predicted those areas that were of greatest risk of ozone damage over the time period. Two methods of risk assessment were compared: the AOT40 (accumulated

concentration above a threshold of 40 parts per billion (ppb)) approach based on the ozone concentration in air above the canopy, and the generic flux approach, which is biologically a more relevant method based on predicting the uptake of ozone through the stomatal pores on the leaf surface. A summary of the main results, including the policy implications, are presented here in accordance with item 3.5 of the 2008 workplan for the implementation of the Convention (ECE/EB.AIR/91/Add.2) adopted by the Executive Body at its twenty-fifth session.

I. SOURCES OF DATA

2. The report on evidence of widespread ozone damage to vegetation in Europe in the period 1990–2006 (Hayes et al. 2007) includes ozone concentration data measured at the local scale at ICP Vegetation monitoring sites together with modelled ozone concentration and flux for 50 km × 50 km grid squares across Europe supplied by EMEP Meteorological Synthesizing Centre-West (MSC-West). Three ozone metrics were used throughout: (a) the 12-hour mean (an average of the ozone concentration between 8 a.m. and 8 p.m.); (b) AOT40 (the accumulation of hourly mean canopy height ozone concentrations above 40 ppb during daylight hours); and (c) $AF_{st}3_{gen}$ (a model of the cumulative flux of ozone into leaves of a generic crop, which takes into account the influence of temperature, light and humidity on the stomatal opening). Evidence of ozone damage was assessed at AOT40 values above the critical level for yield reduction in agricultural crops (an AOT40 of 3 parts per million times hours (ppm h)) and compared with risk maps based on the ozone flux metric, $AF_{st}3_{gen}$. Further information about the critical level and dose metrics used can be found in the *Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends*.

3. The evidence of effects of ambient ozone on vegetation included visible injury records, results from exposure studies in charcoal-filtered/non-filtered air, and visible injury and biomass response data from the ICP Vegetation biomonitoring studies using ozone-sensitive and ozone-resistant biotypes of white clover. Data from peer-reviewed papers and conference proceedings as well as previously unpublished data from ozone research groups across Europe were collated to form a comprehensive database for use in this study.

II. OZONE CLIMATE OF EUROPE

4. Current ozone concentrations vary greatly between regions and years owing to climatic variations, surface topography, landscape and local versus long-distance sources of ozone precursors and other pollutants. The highest ozone concentrations tend to occur in southern Europe, particularly in Greece, Italy, Slovenia, Spain and Switzerland. Moderate ozone concentrations are experienced in other European countries, especially those in central Europe. All European countries are experiencing periodic ozone episodes with several days of peak ozone concentrations exceeding 50 ppb and sometimes exceeding 90 ppb. Maps of ozone flux show that the climatic conditions are conducive to ozone uptake by vegetation across most of Europe, with moderate to high fluxes predicted for some areas such as southern Scandinavia, where ozone concentrations are relatively low.

III. EVIDENCE OF OZONE DAMAGE AT THE EUROPEAN SCALE

5. Visible injury symptoms attributed to ozone pollution were recorded in 16 European countries in the period 1990–2006. The total number of records exceeded 500 and included injury to 30 crop species (e.g. bean, potato, maize, soybean, lettuce) and 80 species of (semi-) natural vegetation encompassing both forbs and grasses. The highest numbers of records were found in Belgium, Greece, Italy, Poland, Spain and Sweden. Unfortunately, it was not possible to analyse spatial or temporal trends in this data set, as the locations where there were the most observations of injury tended to be within easy travelling distance of scientists specializing in ozone effects, rather than found in statistically designed surveys.

6. More detailed analysis was possible for the results of the ICP Vegetation biomonitoring experiments with white clover (1996–2006). Ozone leaf injury scores were generally highest at the sites with the highest AOT40. Across Europe, the ozone injury scores were highest in July and August and lower in June and September, with a few sites recording injury in May and October. The biomass of the sensitive biotype of white clover (NC-S) was significantly reduced relative to that of the ozone-resistant biotype (NC-R) at a number of sites across Europe, especially those in central and southern Europe. NC-S biomass reduction for June-August was linearly related to AOT40 measured at the site ($r^2 = 0.45$ for all data and 0.81 for regional means, figure 1), with the highest reductions at the sites with the highest AOT40 values. Earlier experiments in the period 1994–1996, in which a chemical protectant against ozone injury was applied to *Trifolium subterraneum* (subterranean clover), produced a similar linear relationship with AOT40 when compared with untreated plants.

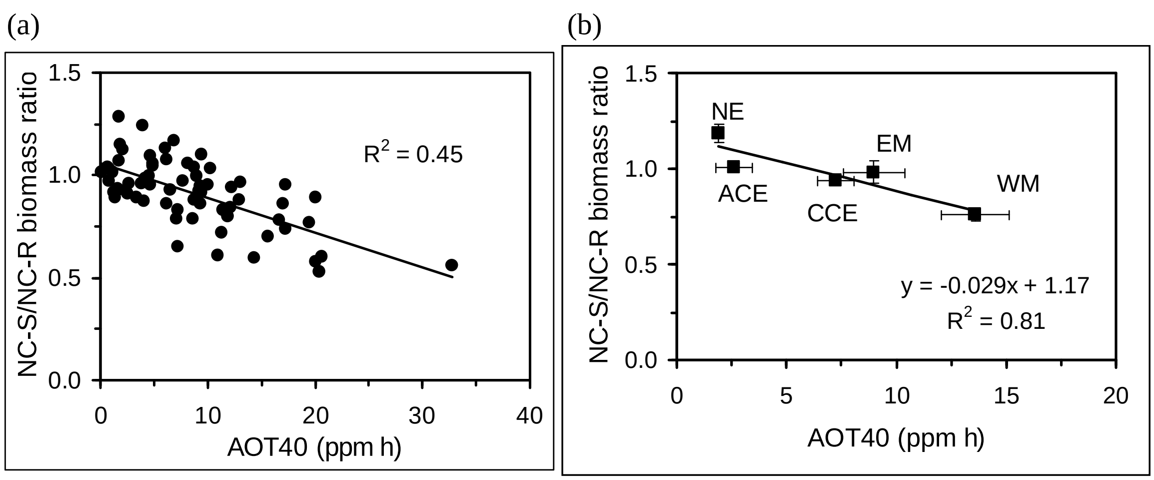

Figure 1. Relationship between three-month AOT40 measured at the site and the biomass of the ozone-sensitive (NC-S) white clover (relative to the ozone-resistant (NC-R) biotype) for (a) all data from ICP Vegetation sites, (b) mean data (± one standard error) for five geographical regions: NE = Northern Europe, ACE = Atlantic Central Europe, CCE = Continental Central Europe, EM = Eastern Mediterranean and WM = Western Mediterranean.

7. In a few experiments, plants were exposed to sub-ambient ozone concentrations using open-top chambers ventilated with charcoal-filtered (CF) ambient air. Biomass reductions of greater than 10% (relative to the CF treatment) were recorded for plants grown in non-filtered (NF) air-ventilated open top chambers at sites in Italy, the Netherlands, Spain and Sweden.

IV. EVIDENCE OF OZONE DAMAGE AT THE REGIONAL SCALE

8. To further analyse the evidence for damaging effects of ozone pollution, the database was divided into the following five geographical regions: Northern Europe, Atlantic Central Europe, Continental Central Europe, Eastern Mediterranean and Western Mediterranean. In Northern Europe, represented by Finland and Sweden, an average of 5% to 25% of NC-S clover leaves were damaged by ozone in 1999 and 2006, whilst between 1% and 5% of leaves were damaged in all the years in between, except in 2005. The highest injury scores detected in Atlantic Central Europe on NC-S clover were in the “high” ozone years of 2003 and 2006. Reductions in biomass in NF- compared to CF-ventilated open-top chambers were detected in Belgium and the Netherlands between 2000 and 2004. Ozone concentrations were higher in Continental Central Europe, with June-August AOT40 values ranging from 0.7 to 13.1 ppm h at ICP Vegetation sites in Austria, Germany, Poland and Switzerland. Interestingly, in this region the highest injury scores on NC-S clover were recorded in the more humid years of 2001 and 2002 rather in than the drier “high” ozone years of 2003 and 2006, suggesting that ozone flux rather than concentration may be more important in determining the magnitude of ozone effect.

9. There were numerous records of ozone injury in Greece and Slovenia, representatives of the Eastern Mediterranean region, with farmers reporting severe value loss in salad crops due to foliar ozone injury rendering the crops unsellable. In the clover biomass experiment, ambient ozone in Greece in 2003 reduced the biomass of NC-S clover by 30% relative to that of the resistant variety. The largest number of reports of the damaging effects of ozone was from the Western Mediterranean region, where the 12-hour mean ozone concentration at ICP Vegetation sites in Italy and Spain was in excess of 40 ppb in each year from 1999 to 2006. Mean ozone injury scores on NC-S clover showed that over 25% of leaves were injured in this region by ozone in 1998 and 2003, with significant injury recorded in all other years. Biomass reductions in NC-S clover were frequently around 20% at many Italian sites. They were as high as 4% and 42% in 1998 and 1999 in Italy (Isola Serafini), when the AOT40 was 20.4 and 32.8 ppm h, respectively.

V. COMPARISON OF EFFECTS IN AMBIENT AIR WITH EMEP RISK MAPS FOR OZONE

10. From the onset, the 2007 report by Hayes et al. set out to answer a series of questions raised by policymakers on the extent of ozone effects in areas identified by the mapping process as being at risk from ozone pollution. Following a consideration of the sources of uncertainty in the data, the results of analysis of effects in ambient air in relation to AOT40 and $AF_{st}3_{gen}$ risk maps of EMEP are summarized by answering policy-specific questions.

A. Sources of uncertainty

11. The sources of uncertainty in this study fall into two main areas: those associated with the quantification of ozone effects and those related to mapping effects in relation to ozone concentration or flux.

12. Ozone injury assessment and biomass reduction for the ICP Vegetation clover experiment was conducted according to a common protocol using plant material supplied by the Coordination Centre, and thus was associated with the least uncertainty. Higher uncertainty was associated with field surveys of injury due to the difficulty of ascertaining the cause of the symptoms. Such uncertainty was minimized in this study by only including data confirmed by ozone exposure experiments or verified by an ozone specialist.

13. Uncertainties associated with the mapping process included:

(a) Simulation of emissions, transport and deposition of ozone (for details, see for example Simpson et al. 2007);
(b) Use of a threshold, with $AF_{st}3_{gen}$ being less sensitive than AOT40 as lower ozone concentrations contribute to this accumulated exposure index than to AOT40;
(c) For the EMEP risk maps time periods earlier in the year than for the ICP Vegetation and other effects data used;
(d) Local factors, including topography, altitude, local emissions, etc., which influenced ozone concentration within an EMEP 50 km × 50 km grid square.

B. Answers to policy questions

14. *Is there any evidence of temporal trends in ozone effects?* At the local scale, there was evidence of higher damage in years with higher ozone concentrations (e.g. 2003 and 2006) in regions of Europe where climatic conditions were conducive to high ozone fluxes. However, the timescale and density of data points were insufficient to allow any long-term trends related, e.g. to the changing ozone profiles (lower peaks, increasing background), to be identified.

15. *Is there evidence of ozone damage in areas of exceedance of the AOT40-based critical level?* Ozone effects were found in central and southern areas of Europe where the EMEP risk maps predict that the AOT40-based critical level for yield reduction was exceeded. AOT40 worked best as a regional-scale indicator of damage: both ozone leaf injury score and biomass reduction were linearly related to the mean EMEP modelled AOT40 for the 50 km × 50 km grid squares the ICP Vegetation sites represented ($r^2 = 0.84$ and 0.97 respectively; see figure 2.b for biomass). Comparison of magnitude of effects at individual sites with EMEP grid square values representing the sites were less conclusive (figure 2.a).

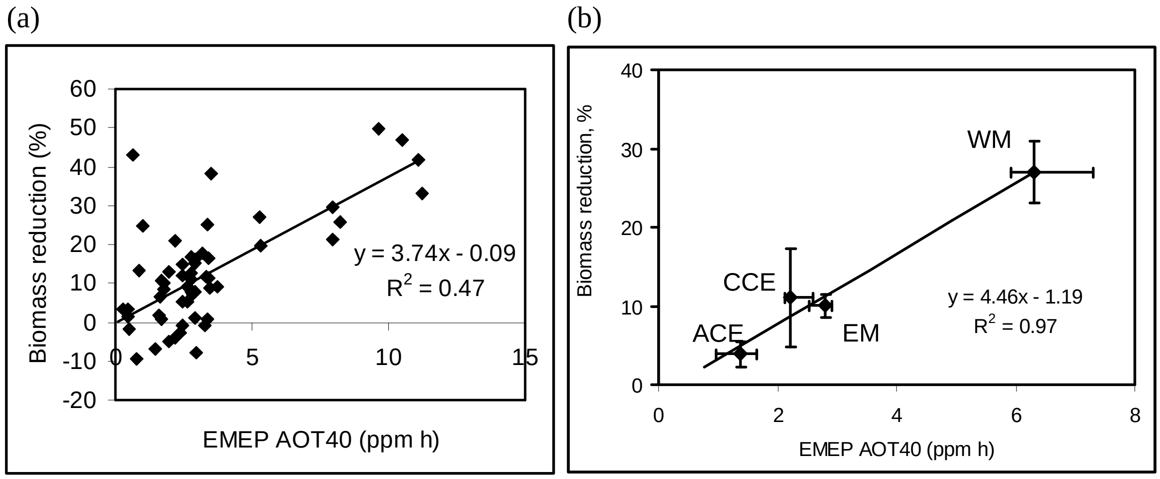

Figure 2. Relationship between percentage biomass reduction in the ozone-sensitive (NC-S) white clover (relative to the ozone-resistant (NC-R) biotype) and: (a) EMEP grid square AOT40 values representing the sites where the experiments were conducted, and (b) mean EMEP AOT40 (± one standard error) for the site grid squares in four geographical regions (see figure 1 for key).

16. *Is there evidence of ozone damage in areas with AOT40s below the critical level?* Ozone damage was found in areas with AOT40 values below the critical level for yield reduction (figure 2). Thus, maps of exceedance of the AOT40-based critical level for agricultural crops (an AOT40 of 3 ppm h) appeared to underestimate the potential for ozone damage in Europe. For example, at the regional scale, the EMEP risk maps indicated that mean AOT40 values were just below the critical level in grid squares representative of Continental Central Europe and Eastern Mediterranean. Yet mean biomass reductions of greater than 10% were recorded in clover in these regions. Furthermore, the critical level for yield reduction did not protect against ozone injury, a response which, in clover at least, occurs at lower AOT40 values than the biomass response. When local evidence of ozone injury on crops and (semi-)natural vegetation was compared with AOT40 maps of EMEP, up to one third of data points were in regions where the maps indicated that the critical level for yield reduction was not exceeded (Hayes et al. 2007).

17. *Does ozone damage occur in areas predicted by the flux-based method to be at risk from ozone effects?* The overriding concept of the generic flux maps is that they indicate risk of ozone damage wherever there is predicted to be any ozone flux to vegetation (i.e. where $AF_{st}3_{gen} > 0$). In this analysis, ozone damage was found in grid squares predicted to have $AF_{st}3_{gen}$ values of at least 5 mmol m^{-2}, with virtually all damage being found in grid squares with an $AF_{st}3_{gen}$ of at least 10 mmol m^{-2} (figure 3). This analysis showed quite clearly that there was either no or minimal impact of ozone in grid squares predicted to have an $AF_{st}3_{gen}$ at or close to zero.

(a) (b)

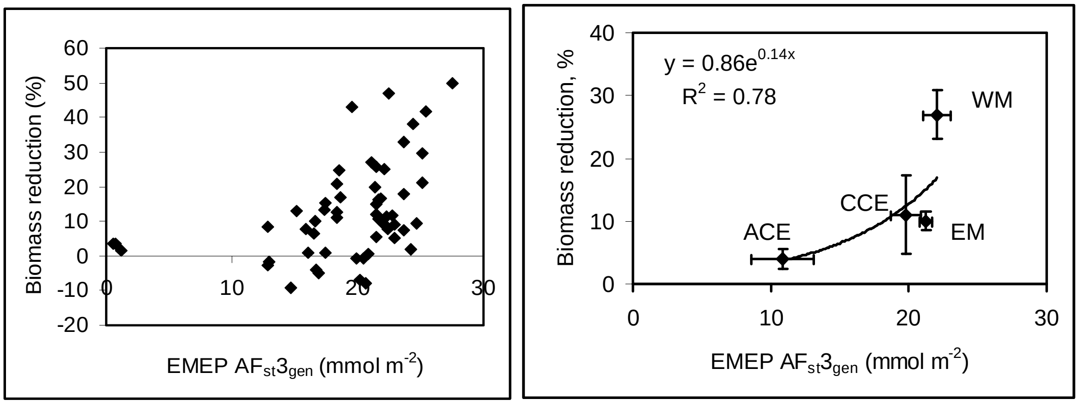

Figure 3. Relationship between percentage biomass reduction in the ozone-sensitive (NC-S) white clover (relative to the ozone-resistant (NC-R) biotype) and (a) EMEP grid square $AF_{st}3_{gen}$ values representing the sites where the experiments were conducted, (b) mean $AF_{st}3_{gen}$ (± one standard error) for the site grid squares in four geographical regions (see figure 1 for abbreviations).

18. *Is there evidence of more ozone damage in the areas with the highest fluxes?* The highest biomass reductions in NC-S white clover were found in grid squares predicted to have an $AF_{st}3_{gen}$ of 18 or more mmol m^{-2} (figure 3), with the highest reduction of nearly 50% being detected in the grid square having the highest predicted $AF_{st}3_{gen}$ of those considered in this study (27.5 mmol m^{-2}). As with AOT40, $AF_{st}3_{gen}$ worked best as a regional-scale indicator, with an exponential relationship between increasing $AF_{st}3_{gen}$ and increasing effect ($r^2 = 0.96$ for injury and 0.78 for biomass reduction, figure 3.b). Local-scale predictions were more susceptible to the uncertainties described above, causing some scatter in the relationship.

19. *Is there evidence of ozone damage in areas with high flux, but low AOT40?* The dose metric, $AF_{st}3_{gen}$ worked particularly well as an indicator of risk of damage in Northern Europe and parts of Atlantic Central Europe. Injury was detected in these regions when $AF_{st}3_{gen}$ values were predicted to be over ca. 10 mmol m^{-2}, but not when $AF_{st}3_{gen}$ values were at or close to zero. According to the AOT40 maps, no injury or yield reduction would have been predicted at these sites because the values were too low (AOT40 was less than 1 ppm h).

20. *Overall, which maps (AOT40 or flux) best predicted areas with ozone damage?* For the reasons described above, maps of the generic flux to crops most accurately predicted the areas where there was evidence of ozone damage. Although AOT40 worked well at the regional scale, effects frequently occurred in areas predicted to be safe from ozone damage (i.e. areas where the AOT40 was below the critical level).

VI. CHALLENGES FOR THE FUTURE

21. There is clear evidence that the ozone profiles over Europe are changing: peak concentrations are declining whilst the background ozone concentration is steadily increasing (Jonson et al. 2005). These changes, coupled with rising temperature, carbon dioxide and changes in precipitation, mean that the AOT40-based and ozone flux-based maps for future decades are very likely to show changes in the distribution and magnitude of predicted effects of ozone across Europe (Simpson et al. 2007). Thus there is a need to further our knowledge of the damaging impacts of ozone on vegetation by:

(a) Spring and summer monitoring of ozone impacts in the field, using an expanded network of sites, including sites in those areas of Europe for which little or no data currently exist;

(b) Developing a long time-series of data for regionally representative sites, to monitor the impacts of changing ozone profiles and climate;

(c) Determining ozone flux-effect relationships for a wider range of crop species and for (semi-)natural vegetation ecosystems, which takes into account the modifying effect of global climate change;

(d) Incorporating consideration of effects of soil moisture deficit as a key modifying factor of stomatal conductance into risk assessment maps for crops and (semi-)natural vegetation;

(e) Developing the next generation of ozone risk maps, which should include the modifying influence of climate change (e.g. temperature, increasing carbon dioxide concentration, changing precipitation patterns), and by collating suitable field-based data for evaluation of these new maps.

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[1] The references have been reproduced as received by the secretariat.