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**IMPACTS OF OZONE ON VEGETATION IN A CHANGING CLIMATE**

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

**INTRODUCTION**

1. Many studies have been conducted on the impacts of ozone (O<sub>3</sub>) pollution on vegetation. The studies have ranged from examining effects at the (sub-)cellular level to predicting impacts on a regional and international scale. However, it has become increasingly important, when predicting future impacts of O<sub>3</sub>, to consider them within the context of global climate change rather than in isolation.
2. Current levels of tropospheric O<sub>3</sub> have been shown to damage crops, trees and (semi-)natural vegetation. Effects-based research has resulted in the establishment of critical levels of O<sub>3</sub> for vegetation. Historically, these critical levels were based on the concentration of

O<sub>3</sub> in the atmosphere. It was long recognized that plant responses to O<sub>3</sub> were more closely related to the absorbed O<sub>3</sub> dose, or the instantaneous flux of O<sub>3</sub> through the stomata. Recently, stomatal flux-based critical levels of O<sub>3</sub> were defined for selected crop species and provisionally for trees (ICP Modelling and Mapping, 2004). Stomatal flux-based critical levels of O<sub>3</sub> took into account the varying influences of temperature, water vapour pressure deficit (VPD), light, soil water potential (SWP), atmospheric O<sub>3</sub> concentration and plant development (phenology) on O<sub>3</sub> uptake. As such, they have lent themselves to understanding impacts under climate change conditions, since factors such as elevated carbon dioxide (CO<sub>2</sub>), temperature and changes in precipitation affect the stomatal flux of O<sub>3</sub> into leaves via direct or indirect impacts on stomatal conductance (g<sub>s</sub>). In contrast to the concentration-based approach, the principles of the flux-based approach allowed climate change factors to be incorporated into assessments of critical levels. It was important to understand that such factors might not only act as “dose modifiers” but also influence the detoxification capacity of the plant, among other factors.

3. Emission scenarios applied by the Intergovernmental Panel on Climate Change (IPCC) projected globally that by the end of the twenty-first century the mean tropospheric background O<sub>3</sub> concentration would change by between -2 and +62%, the mean temperature would increase between 1.4 and 5.8°C, the carbon dioxide (CO<sub>2</sub>) concentration would increase to 540–970 parts per million (ppm), precipitation patterns across the globe would alter and the frequency of extreme events would increase. Vingarzan (2004), using different IPCC scenarios, predicted future global mean background tropospheric O<sub>3</sub> concentrations ranging from about 40 to 80 parts per billion (ppb). There was evidence that in Europe the mean ground-level O<sub>3</sub> concentrations were increasing and the peak concentrations were declining. In the future, peak concentrations of O<sub>3</sub> will probably be reduced further with the implementation of the 1999 Gothenburg Protocol, but this should be considered in the context of an increasing global background concentration.

4. The overall impact of warming on the canopy O<sub>3</sub> flux was difficult to predict and would depend on, for example, the location of the vegetation, the severity and timing of warming, and its impacts on SWP and plant phenology (including the growth period, canopy development and the leaf area index). Plant species often had an optimal temperature range for g (ICP Modelling and Mapping, 2004) and might acclimatize to warming within this range, depending on local environmental conditions. Warming might encourage earlier and enhanced plant development, resulting in a forward shift of the period within the year when plants were absorbing O<sub>3</sub>. This might lead to a change in the stomatal O<sub>3</sub> flux if peak O<sub>3</sub> concentrations, currently associated with midsummer, coincided with a later developmental stage of the plants. Little empirical data were available on the interactive impacts of O<sub>3</sub> and warming on vegetation, in particular at the field scale.

5. Many studies showed that atmospheric CO<sub>2</sub> enrichment reduces g<sub>s</sub>. Although it was suggested that acclimatization of g<sub>s</sub> to long-term exposure to elevated CO<sub>2</sub> might occur, this was not substantiated by conclusive evidence. Therefore, when plants were exposed to O<sub>3</sub> in the presence of elevated CO<sub>2</sub>, the uptake of O<sub>3</sub> was often reduced. In general, elevated CO<sub>2</sub> ameliorated O<sub>3</sub>-induced stress and elevated O<sub>3</sub> offsets or moderates responses induced by elevated CO<sub>2</sub>, as elevated CO<sub>2</sub> and O<sub>3</sub> affect vegetation in opposing ways (Fuhrer, 2003; Karnosky et al., 2003).

6. Effects of changes in precipitation patterns are likely to be mediated through (a) effects of VPD on g<sub>s</sub>, with increasing VPD causing a decrease in flux and (b) changes in SWP, with decreasing SWP resulting in decreased stomatal flux (ICP Modelling and Mapping, 2004).

## I. A MODELLING CASE STUDY FOR WINTER WHEAT

7. A modelling case study was conducted for winter wheat (*Triticum aestivum*). Annual hourly O<sub>3</sub> concentrations at a height of 50 m and canopy height (i.e. 1 m) and meteorological data near the canopy surface were provided by the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe / Meteorological Synthesizing Centre - West (EMEP/MSC-W) for the year 1997 for five selected EMEP grid cells. They represented the five climate zones in Europe, as described in the *Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends* (ICP Modelling and Mapping, 2004). The stomatal flux model described in the *Mapping manual*, which is based on the stomatal component of the model on the deposition of ozone and stomatal exchange (DO<sub>3</sub>SE) (Emberson et al., 2006), was applied to calculate the accumulated stomatal flux of O<sub>3</sub> above a threshold of 6 nmol m<sup>-2</sup> projected leaf area (PLA) s<sup>-1</sup> (AF<sub>st6</sub>) for winter wheat. The core of the leaf ozone flux model was the stomatal conductance (g<sub>sto</sub>) multiplicative algorithm:

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

where g<sub>sto</sub> was the actual stomatal conductance (mmol O<sub>3</sub> m<sup>-2</sup> PLA s<sup>-1</sup>) and g<sub>max</sub> was the species-specific maximum stomatal conductance (mmol O<sub>3</sub> m<sup>-2</sup> PLA s<sup>-1</sup>). The parameters f<sub>phen</sub>, f<sub>O3</sub>, f<sub>light</sub>, f<sub>temp</sub>, f<sub>VPD</sub> and f<sub>SWP</sub> were all expressed in relative terms (i.e. they took values between 0 and 1) as a proportion of g<sub>max</sub>. These parameters allowed for the modifying influence of phenology (phen) and ozone and four environmental variables (light (irradiance), temperature, atmospheric vapour pressure deficit (VPD) and soil water potential (SWP)) on stomatal conductance to be estimated. A simple “water budget” modelling approach was used to estimate soil moisture deficit (SMD). This method used the multiplicative models estimation of canopy g<sub>sto</sub> in conjunction with the atmospheric water deficit to estimate the actual canopy transpiration. Thus the modelling of the accumulation of SMD, the resulting SWP and influence on g<sub>sto</sub> (determined according to species

and/or cover-type-specific  $f_{swp}$ , soil type and rooting depth) was modelled in an internally consistent manner.

8. The stomatal  $DO_3SE$  model was run with both current (1997) and climate change input  $O_3$  and meteorological data. For the climate change model runs, the current year (1997) input data were modified as described in table 1, both with (CC+ $O_3$ ) and without (CC) an increase in the  $O_3$  concentration, to understand the effects on stomatal  $O_3$  flux attributable to climate separately from those resulting from changes in  $O_3$  concentration. The applied climate scenario reflected mean global changes as predicted for the end of the twenty-first century. The impact of elevated  $CO_2$  on stomatal conductance was incorporated into the  $DO_3SE$  model by multiplying  $g_{max}$  with a factor of 0.65, based on the measured reduction of  $g_{max}$  in a free air carbon dioxide enrichment (FACE) study with spring wheat, where  $CO_2$  concentrations were raised to 550 ppm. For precipitation, no changes or small increases (10%) in the hourly amount of precipitation, depending on climate zone, were included, with no changes in the frequency. Modification to the VPD was achieved assuming a constant absolute humidity and a 3°C rise in temperature. Since the uncertainty in estimating a change in VPD was high, and some model predictions suggested water vapour concentrations would increase, two model runs were performed: (a) without modifying VPD and (b) with modification of VPD (indicated by (VPD)). It would have been possible to apply more specific and localized scenarios of climate change in these simulations, but, because the uncertainty in regional predictions was so great, it was decided to compare the effect of the same changes at different locations in Europe.

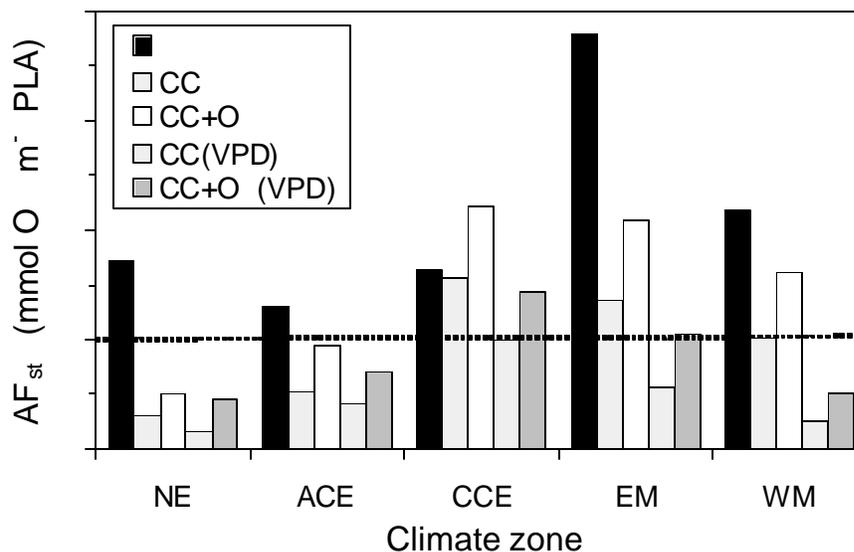
**Table 1.** Modifications to current day (1997) meteorological and  $O_3$  concentration input data for climate change conditions

Parameter	Climate change (CC)	Climate change + $O_3$ increase (CC+ $O_3$ )
[ $O_3$ ] (ppb)	No change in $O_3$ concentration	Increase $O_3$ concentration by 5 ppb in all hours of the day
Temperature (°C)	+3°C	+3°C
$CO_2$ effect on $g$	$g_{max} * 0.65$	$g_{max} * 0.65$
Precipitation (P) (mm) <sup>1</sup>	If P > 0, increase P by 10% in northern and central Europe	If P > 0, increase P by 10% in northern and central Europe
VPD (kPa)	Assume absolute humidity remains constant, calculate VPD according to increase in temperature by 3°C	Assume absolute humidity remains constant, calculate VPD according to increase in temperature by 3°C

<sup>1</sup> Only hourly P events were altered; that is, the magnitude and not the frequency of P events was increased.

9. In addition to predicted changes in  $AF_{st6}$ , the accumulated  $O_3$  concentration above a threshold of 40 ppb during daylight hours (AOT40) was estimated using the climate-specific accumulation windows, which were not altered for climate change conditions, given in the *Mapping manual*. The future AOT40 at canopy height was estimated from canopy height  $O_3$  concentrations. These were derived from the 50 m height  $O_3$  concentration data with an increase of 5 ppb either by (a) simply adding 5 ppb to the EMEP  $O_3$  concentration output at canopy height or (b) estimating the canopy  $O_3$  concentrations using the neutral stability method described in the *Mapping manual*. This allowed “climate change” canopy  $g$  values to be incorporated into the assessment of the  $O_3$  concentration profile and hence investigation of the effect that climate change might have on AOT40 via changes in  $O_3$  deposition to vegetated surfaces.

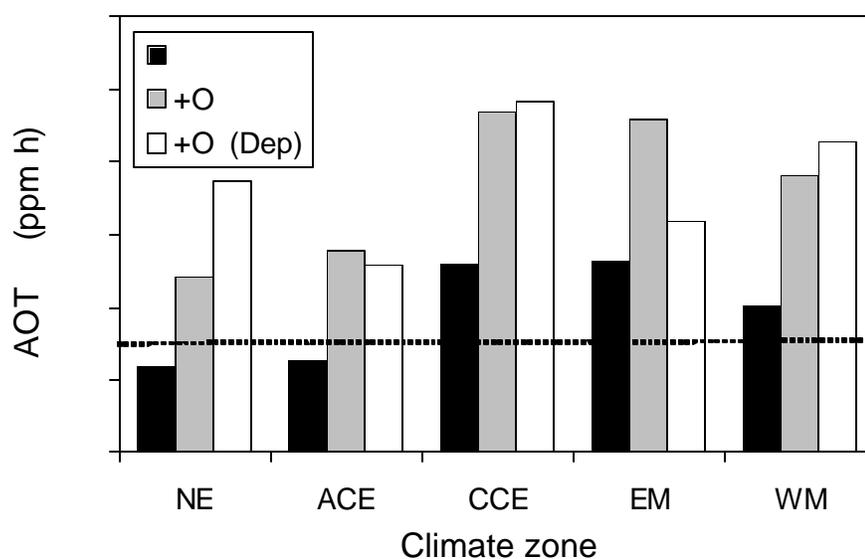
## II. RESULTS OF THE MODELLING CASE STUDY



**Figure 1.** Modelled accumulated stomatal flux of  $O_3$  above a threshold of  $6 \text{ nmol m}^{-2} \text{ PLA s}^{-1}$  ( $AF_{st6}$ ) for winter wheat for five different climate zones in Europe for the reference year 1997 and for future climate using the climate change scenarios (see text) described in table 1. The dashed line indicates the flux-based critical level of  $O_3$  for wheat ( $AF_{st6} = 1 \text{ mmol m}^{-2} \text{ PLA}$ ). Abbreviations for climate zones are: NE = Northern Europe, ACE = Atlantic Central Europe, CCE = Continental Central Europe, EM = Eastern Mediterranean, WM = Western Mediterranean.

10. In interpreting the results for the five climate zones in Europe, it should be noted that that the model runs were performed for only one selected EMEP grid cell within each climate zone. Application of the climate change scenarios (“CC”) resulted in a decrease of the  $AF_{st6}$  for winter wheat (even with an increase in tropospheric background  $O_3$  concentration: “CC+ $O_3$ ”) for most

of Europe, but not for Continental Central Europe (figure 1). The model predicted that an increase in VPD would result in a significant decrease in the  $AF_{st6}$  for winter wheat. This was due to the direct limiting influence on  $g$ , but also related to the influence VPD had on determining SMD. SMD was the key driver limiting flux under the current and “CC+O<sub>3</sub> (VPD)” model runs in Northern Europe and the Western Mediterranean. The high SMD in Northern Europe was a result of the high VPDs (higher than in other parts of Europe due to the later growing season, even with the 3°C increase in temperature) causing rapid water movement from the soil to the atmosphere through the plant, and this was not negated by the 10% increase in the amount of precipitation. For the Western Mediterranean the higher VPDs again resulted in higher SMD. However, Continental Central Europe had SMD limitation under current but not future climate conditions, which was primarily due to the shifting of the growth period to earlier in the year, which coincided with heavier precipitation events. This explained why the  $AF_{st6}$  for winter wheat did not decrease in Continental Central Europe under the “CC” scenario compared to the current year (1997)  $AF_{st6}$ . Performing the model runs with no changes in precipitation for Northern and Central Europe hardly affected the outcome. The use of the thermal time method to estimate both the timing of mid-anthesis and the start and end of the growing season meant that with global warming the growth and accumulation period started and ended earlier at each location (Harmens et al., 2006).



**Figure 2.** Impact of the climate change (“CC+O<sub>3</sub> (VPD)” scenario; see table 1) in comparison with the current day (1997) climate on  $f_{SWP}$  for winter wheat for five different climate zones in Europe (see figure 1 for details). Data are not shown for the climate zones with an  $f_{SWP} = 1$  throughout the year.

11. In general, the total O<sub>3</sub> deposition in a future climate was reduced due to the reduction in stomatal flux (which also translated into reduced flux of upper-canopy leaves and the lower

AF<sub>st6</sub> values reported in figure 1), which meant that less O<sub>3</sub> is lost from the atmosphere to the vegetation. This reduction in stomatal flux and hence total deposition would result in higher atmospheric O<sub>3</sub> concentrations, which would likely lead to higher AOT40s. Figure 2 shows such a situation occurring in Northern Europe, Continental Central Europe and the Western Mediterranean. However, for Atlantic Central Europe and the Eastern Mediterranean, this was not the case, since the earlier AOT40 accumulation periods recommended for these climate zones coincided with periods when the deposition under climate change conditions was higher than the current deposition. This was because the earlier growth period of wheat under climate change (estimated using the thermal time model) occurred under conditions less limiting to g (i.e. lower temperatures and VPDs).

### III. GENERAL DISCUSSION

12. Based on the modelling case study for winter wheat, two contrasting conclusions could be drawn from the application of a flux-based compared to a concentration-based risk assessment methodology in a changing climate: (a) The flux-based approach predicts a reduction in the absorbed O<sub>3</sub> dose for winter wheat under climate change conditions in most areas of Europe, resulting in reduced exceedance of the flux-based critical level; (b) the concentration-based approach predicts a considerable increase in concentration-based critical level exceedance under future climate conditions. These trends were generally observed across a variety of climates in Europe, despite the fact that the modelling was only applied to one grid cell per climate zone. In the case of the concentration-based approach, the simple modelling conducted here suggested that such exceedance may be exacerbated in some locations due to the effect of reduced O<sub>3</sub> deposition to vegetated surfaces. However, the enhancement of leaf area index, which might occur for some species under climate change conditions, was not included and would certainly reduce the estimated decreases in deposition to the vegetated surface.

13. The simulations were based on simple assumptions about possible changes in climate and O<sub>3</sub> exposure in Europe in coming decades. They were not intended to be predictions of the relative effects in different regions. Nevertheless, applying the model to different locations showed important differences in response that allowed better understanding of the influence of key factors in modifying stomatal O<sub>3</sub> flux in a changing climate. A number of other factors could have been considered. For example, O<sub>3</sub> exposure patterns in a changing climate might change in several ways. Firstly, tropospheric background O<sub>3</sub> increases would not be constant throughout the year, as the peaks in tropospheric background occurred in spring rather than midsummer; this might offset the benefits of an earlier start to the growing season. Secondly, increased surface temperatures might lead to increased biogenic volatile organic compound (VOC) emissions and hence greater regional O<sub>3</sub> production. These and other factors strongly suggest the need to incorporate a deposition and flux model into atmospheric chemistry/transport models so that the combined effects of climate on O<sub>3</sub> formation, transport, deposition and impacts can be assessed

in an integrated fashion. Finally, the results presented are for one determinate crop species and should not be taken as predictive of the response of other species.

14. O<sub>3</sub> effects studied in isolation were used to establish dose-response or flux-effect relationships. However, in predicting future impacts of O<sub>3</sub>, it became increasingly important to consider O<sub>3</sub> effects within the context of global climate change. Vegetation responses to climate change were driven by complex interactions between abiotic and biotic factors such as atmospheric CO<sub>2</sub>, temperature, nutrient and water availability, atmospheric pollutants, soil characteristics, land use/management and species composition/diversity, and were difficult to predict. Vegetation responses to single drivers of climate change (including changes in tropospheric O<sub>3</sub> concentrations) could not simply be scaled up to responses to multiple drivers. There was a clear need for an approach combining multifactorial experiments and modelling to improve predictions of the long-term impact of climate change on plant communities. Elevated O<sub>3</sub> at relatively low concentrations could significantly reduce the enhancement of growth by elevated CO<sub>2</sub> and therefore reduce carbon sequestration. This might mean that worldwide growth stimulations would not be as great as predicted from previous experimental and modelling studies with only elevated CO<sub>2</sub> (i.e. without elevated O<sub>3</sub> as a co-factor). Therefore, it was also important to bring an understanding of O<sub>3</sub> as a moderator of climate change responses into global models of terrestrial net primary productivity and carbon sequestration.

15. More knowledge was needed on the responses of plant communities to O<sub>3</sub> in a changing climate, because species competition was likely to influence the effects of O<sub>3</sub> and climate change on individual plant species. Climate change was also expected to affect the temporal and spatial association between species interacting at different trophic levels (e.g. plant-insect and plant-disease interactions) (Fuhrer, 2003; Karnosky et al., 2003).

#### IV. CONCLUSIONS AND RECOMMENDATIONS

16. In contrast to the concentration-based approach, the principles of the flux-based approach allowed some key climate change factors to be incorporated into assessments of O<sub>3</sub> critical levels for vegetation. Results of a case study for winter wheat indicated that in a future climate the exceedance of the flux-based critical level of O<sub>3</sub> might be reduced across Europe, even when taking into account an increase in tropospheric O<sub>3</sub> concentration. In contrast, the exceedance of the concentration-based critical level of O<sub>3</sub> might increase due both to anthropogenically induced increases in background tropospheric O<sub>3</sub> concentration and alterations to the O<sub>3</sub> mass balance resulting from reduced O<sub>3</sub> deposition rates.

17. Climate change factors should be fully incorporated into the O<sub>3</sub> risk assessment methodology. The influence of climate change should be considered when predicting the future effects of O<sub>3</sub> on vegetation (and vice versa).

18. There was a clear need for multi-factorial experiments at the field scale to provide improved information for O<sub>3</sub> flux-effect modelling for the current and future climate. The DO<sub>3</sub>SE model was a useful tool for predicting the stomatal flux of ozone, but multi-factorial experiments at the field scale were needed to improve parameterization for the current and future climate.

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