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NEW DIRECTIONS

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New Directions: A new generation of ozone critical levels for the protection of vegetation in Europe ☆

Ozone is the most important air pollutant affecting vegetation. In Europe, the AOT40 index, based on cumulative exposure of ambient ozone concentrations above 40 ppb, has been adopted for use within the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Trans-boundary Air Pollution (CLRTAP) and the European Union. However, the limitations of indices based on external concentrations have long been recognised. At the CLRTAP workshop in Gothenburg, 2002 (Bull et al., 2003, at http://www.ozoneworkshop.ivl.se/wsreport.htm), two alternative approaches were considered, based on modeled stomatal ozone flux and on the maximum permissible ozone concentration (MPOC). Here we present an assessment of the strengths and weaknesses of each approach from the scientific perspective, as well as from a perspective of continental-scale regional risk assessment and policy evaluation.

The major break-through leading to the adoption of AOT40 was made at the CLRTAP ozone workshop in Bern in 1993, where it was demonstrated that the negative effects of ozone on yields of wheat could be well related to the daylight AOT40 index. Based on this result, a new set of ozone critical levels for agricultural crops were agreed upon at the subsequent CLRTAP critical levels workshop in Kuopio in 1996. At the same time, the daylight AOT40 index was adopted also to define critical levels for trees and semi-natural vegetation.

There has been a growing consensus that the effective ozone dose based on stomatal ozone flux (rate of ozone uptake through the microscopic stomatal pores into the leaves) represents the most appropriate approach for setting future ozone critical levels for vegetation in Europe. The stomatal ozone flux can be estimated as the product of the ozone concentration close to the leaves or needles and the inverse of the sum of resistances along the ozone diffusion pathway to the site of action within the leaf interior. Under most conditions, the stomatal conductance (inverse stomatal resistance) is the most important conductance for ozone flux to leaves. A new deposition module has been developed and incorporated into the European Modelling and Evaluation Programme (EMEP) photochemical model that uses a multiplicative simulation model to estimate stomatal conductance (Ashmore, 2003, at http://www.ozoneworkshop.ivl.se). Preliminary runs with the EMEP model indicate that the spatial patterns over Europe for daylight AOT40 and for accumulated stomatal flux of ozone may be very different (Simpson et al., 2003, at http://www.ozoneworkshop.ivl.se).

The major advantage in using the ozone flux rather than concentration-based approaches is that the very substantial influence of climatic variables on ozone uptake is included. It has been shown that the inter-annual variation in ozone sensitivity of wheat can largely be explained by the influence of climate on ozone uptake (Pleijel et al., 2000, Environmental Pollution 109, 453–462). Dose-response relationships between relative yield and cumulative ozone flux have been developed for wheat and potato and included in the Mapping Manual of the CLRTAP. They perform better in statistical terms than the AOT40 relationships based on the same data set (http://www.icpmapping.org, Chapter 3). Also, for the short-term critical level to protect sensitive vegetation from visible leaf injury, the flux-based approach outperforms the AOT40 concept. To date, results from re-calculated data do not indicate that a flux-based approach represents an advantage over the AOT40 approach in explaining growth responses to ozone by young trees in controlled experiments (Karlsson et al., 2003, at http://www.ozoneworkshop.ivl.se). However, field studies from Bavaria with mature trees provide evidence that stomatal flux is a better predictor of injury than is AOT40.

Statistical analysis clearly shows that the relationships with the highest correlations between effect and exposure have been obtained using ozone exposure indices with thresholds. More importantly, on a biochemical level there is overwhelming evidence that a degree of ozone detoxification capacity exists in plant leaves, consistent with the concept of a threshold. However, the use of thresholds, whether as concentration or modeled

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flux, is a major source of uncertainty in large-scale modelling of ozone exposure. The problem is particularly large when the thresholds are close to background levels, as is the case in many parts of northern Europe.

The major difficulty with the ozone flux approach is the extensive datasets required for its application. As such, simplification of the existing algorithms and associated data needs would constitute an extremely valuable future methodological development. Furthermore, establishing field validations of the ozone flux-response relationships currently derived mainly from experimental conditions should be seen as a priority for future research.

A third concept of risk assessment has been suggested, based on maximum permissible O_3 concentrations to protect vegetation (MPOC, Krause et al., 2003, at http://www.ozoneworkshop.ivl.se). The MPOC allows classification of the probability for adverse plant response to ozone exposure and defines critical mean ozone concentrations for different averaging times. MPOC uses a mix of response parameters and species, which makes the consequences of exceedance of MPOC values unclear. Ozone flux is relevant to the MPOC risk assessment only when estimating the ozone concentration at the canopy level, using monitoring data from different heights. When the ozone flux rate is high, the concentration at canopy level becomes lower, all other factors being constant. Thus, according to the MPOC concept, the estimated risk for ozone injury will be smaller if the ozone flux is larger, for example to an irrigated field crop, as compared to a nearby field crop experiencing drought. This inverse relationship between stomatal uptake of ozone and MPOC risk assessment is a major shortcoming of the method.

At present, flux-based critical levels have been established for wheat, potato and provisionally for sensitive deciduous trees. AOT40 based critical levels will remain in use for crops, as well as for forests, until that time when the methods are appropriately advanced for application to additional species. The flux approach provides a much stronger mechanistic basis for ozone risk assessment, but is more data intensive. Future development of the flux approach to link variable stomatal flux to variable rates of ozone detoxification offers the potential to greatly enhance our capacity to predict responses of vegetation to ozone under a range of growth conditions across Europe.

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