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Air Pollutant Combinations – Significance for Future Impact Assessments on Vegetation

By

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Summary

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Research on combinations of "classical" air pollutants such as SO_2, NO_x, acid deposition or O_3 has extensively been carried out in the eighties and early nineties of the last century. More recently, attention has been paid to the interactions between elevated CO_2 concentrations and air pollutants since the importance of the direct effects of rising CO_2 on vegetation on a global scale has been recognized and since there is evidence that elevated CO_2 has the potential to mitigate negative effects of air pollutants. A short synopsis is provided of the state of the scientific knowledge on the effects of pollutant mixtures on vegetation focussing on combinations with O_3. Particular emphasis is laid on current uncertainties and gaps in assessing pollutant interactions involved in the modification of plant responses to predicted changes in climate and atmosphere.

Introduction

Most studies on the impact of pollutant mixtures on plants are older than 10 years and have been confined to a limited number of gaseous air pollutants such as SO_2, NO_2, and O_3 (RUNECKLES 1984, KOHUT 1985, MANSFIELD & MCCUNE 1988). This is mainly because the air pollution climate up to 1990s was characterized by the widespread occurrence of high atmospheric concentrations of the primary pollutants SO_2 and NO_2 in addition to acidic deposition and high levels of O_3, i.e. these pollutants were recognized as being a major part of the pollution problems in Europe and North America. In addition, most of these early studies

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with pollutant combinations involved short-term exposures at acute pollutant concentrations. However, the pollution climate in many parts of the industrialized world has changed during the past decades (DÄMMGEN & WEIGEL 1998). For example, concentrations of SO_2 have considerably declined and higher levels of SO_2 are usually restricted to wintertime when energy demand is high. In contrast, ground-level O_3 concentrations remain to be the most significant threat to vegetation during the growing season, so more recent research on pollutant combinations has primarily focussed on interactions of O_3, mainly with one other pollutant (BENDER & WEIGEL 1993, BARNES & WELLBURN 1998). However, an assessment of the impact of O_3 on the vegetation in a future pollution climate has to consider the concomitant rise in atmospheric CO_2, as potentially damaging photochemical episodes will undoubtedly occur against a background of higher atmospheric CO_2 concentrations. Thus, the objectives of this paper are: (1) to briefly discuss the current knowledge concerning interactive effects of pollutant mixtures focussing on pollutant combinations with O_3; and (2) to discuss our understanding on the interactive effects of O_3 and CO_2 on the basis of recent findings from pan-European research projects.

Pollutant Interaction Studies with Ozone: A Brief Summary

There are numerous reports of the effects of O_3 in concert with other pollutants such as SO_2, NO_2 or acid deposition on plants, however, most of the studies dealing with pollutant mixtures are older than 10 years (e.g. reviewed by RUNECKLES 1984, REINERT 1984, MANSFIELD & MCCUNE 1988, WOLFENDEN & al. 1992). On a whole, the majority of these studies are not very useful for impact assessments of present-day pollution climates because of the unrealistic exposure levels and the atypical exposure profiles used. Currently, for example, a simultaneous occurrence of air pollutants such as O_3, SO_2, NO_2 or NH_3 at phytotoxic levels is rather unusual, i.e. that co-occurrences are only of short duration and far less frequent than sequential or combined sequential/concurrent exposures. Particularly, concentrations of NO_2 and O_3 (both constituents of photochemical smog) vary during the day in patterns that normally result in sequential exposures. Previous studies with mixtures of O_3 and NO_2 were carried out under simultaneous rather than sequential exposure regimes of both gases, and plants were usually exposed for a short period of days or weeks to high pollutant levels. Such exposure regimes have often been found to result in synergistic (more-than-additive) effects on plants (GUDERIAN & TINGEY 1987). In contrast, more realistic experiments using sequential exposures and near-ambient pollutant concentrations provided only little evidence of statistically significant interactions (i.e. additive effects predominate). When interactions were observed, the mode of interaction was mostly antagonistic, i.e. the presence of NO_2 counteracted the effects of O_3 (BENDER & WEIGEL 1994). BARNES & WELLBURN 1998 and FANGMEIER & al. 2002 discuss experiments where exposure conditions have been more realistic in terms of their likelihood of occurrence in ambient air in two recent reviews. The major results from their literature reviews on the effects of pollutant mixtures are compiled in Table 1.

Table 1. Simplified summary of effects of O_3 in combination with other pollutants.

Pollutant mixture	Combined effect	Species most frequently investigated
$O_3 + SO_2$	Both synergistic and antagonistic	Crops, forest trees
$O_3 + NH_3$	Mostly antagonistic (at low [NH_3] or additive	Forest trees
$O_3 + NO_2$	Synergistic at high concentrations, antagonistic at low conc.	Crops and vegetables
O_3 + acid deposition	Mostly additive, sometimes antagonistic	Forest trees
$O_3 + NO_2 + SO_2$	No consistent response across different studies	Forest trees, crops, natural vegetation

Some general trends can be derived from the existing work: (1) additive effects seem to be more frequent than statistically significant interactions, (2) antagonistic interactions are tend to be found when gases were applied sequentially (e.g. O_3/NO_2) and/or when e.g. nitrogenous or sulfurous air pollutants were combined with O_3 at relatively low levels, suggesting that plants were able to utilize the additional sulfur or nitrogen source, and, (3) synergistic interactions are more likely to be found when O_3 was applied simultaneously with another pollutant at high concentrations. However, generalizations of the long-term effects on pollutant mixtures at relevant concentrations on particular plants are not possible, because of the diversity and variability of responses, depending on species, cultivars, stage of development, concentration and ratio of the pollutant in mixtures, and structure of exposure. Furthermore, hardly any existing exposure system is suitable to run multi-factorial experiments with a sufficient number of treatments and of treatment replications, which is particularly true when more than two pollutants should be included. FANGMEIER & al. 2002 therefore concluded that there is no realistic chance for a substantial improvement of the current knowledge by the sole use of experimental investigations.

Elevated CO_2 and Interactions with O_3

Concerns about global warming and the role of rising atmospheric CO_2 and tropospheric O_3 as components of global climate change have triggered recent research interest on the interactions of O_3 with increased levels of CO_2. The importance of considering concomitant changes in the atmospheric CO_2 concentration and O_3 in the prediction of plant responses to a changing climate was already emphasized by KRUPA & KICKERT 1989 and ALLEN 1990. Numerous studies have demonstrated that elevated CO_2 levels stimulate the rate of photosynthesis, reduce the rate of photorespiration, and enhance plant growth and productivity, and thus affect most plant processes in the opposite direction than O_3. Also, exposure to elevated CO_2 generally reduces stomatal conductance thus restricting the flux of O_3 into leaves. ALLEN 1990 therefore assumed that partial stomatal closure induced by high CO_2 may reduce the impacts of O_3 (i.e. making plants less susceptible to O_3), and there is indeed some experimental evidence to support this view (RAO & al. 1995, RUDORFF & al. 1996, MCKEE & al. 1997, HUDAK & al. 1999). HEAGLE & al. 1993 have shown, however, that the protection afforded by elevated CO_2 can diminish after prolonged O_3 exposure, and MCKEE & al. 1997 found that elevated CO_2 provided full protection against the detrimental effects of O_3 on wheat biomass, but not on yield. In contrast, BARNES & al. 1995 found no protection against O_3 in elevated CO_2-grown wheat, and suggested that CO_2 enrichment might plants more susceptible to O_3 damage at the cellular level. These few examples from isolated experiments illustrate that no consistent interaction between O_3 and CO_2 exist. However, there are two coordinated European projects that have more focussed on the systematic investigation on the interaction between elevated CO_2 and O_3.

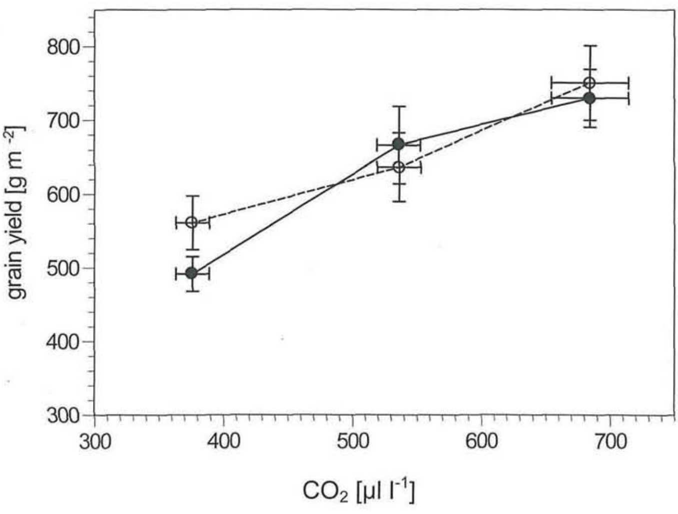

Fig. 1. Grain yield of spring wheat (*Triticum aestivum* L. cv. Minaret) as affected by CO_2 and O_3 (data compiled from BENDER & al. 1999, including 13 different OTC experiments at 5 European sites). Open symbols: ambient O_3 (12 hr mean = 32.5 nl l^{-1}); closed symbols: high O_3 (12 hr mean = 60.3 nl l^{-1}). PCO_2: < 0.001; PO_3: n.s. (0.374); PCO_2xO_3: n.s. (0.389).

The ESPACE-Wheat project (European Stress Physiology and Climate Experiment – Project 1: Wheat) was carried out for three consecutive growing seasons at eight experimental field sites across Europe (JÄGER & al. 1999), yielding 13 individual field exposure experiments on the interactive effects of CO_2 enrichment and ozone on growth and yield of spring wheat (*Triticum aestivum* L. cv. Minaret) exposed in open-top field chambers (OTC). The average yield data of these experiments are shown in Fig. 1. These data suggest some protective effects of CO_2 enrichment against yield loss due to high ozone exposure, however, the overall statistical analysis did not reveal any significant interactions. Out of the 13 individual data sets used in Fig. 1, only 2 showed significant CO_2 x O_3 interactions on wheat yield (BENDER & al. 1999). A similar experimental approach was involved in a later trans-European study to test the response of potato (*Solanum tuberosum* L. cv. Bintje) to CO_2 enrichment and tropospheric ozone within the CHIP project (Climate Change and Potential Impact on Potato Yield and Quality). Six individual data sets from 3 field exposure sites involving OTC were used to illustrate the effects of CO_2 and O_3 as shown in Fig. 2. Since variation of tuber yield data between sites was considerably high because of climatic differences (DE TEMMERMAN & al. 2002), normalized data expressed as % yield of control (OTC with ambient air) have been calculated. Potato yield was less responsive to CO_2 enrichment than wheat yield, and saturation of CO_2 response was reached within the range of concentrations applied in the CHIP experiments. The data shown in Fig. 2 suggest a protective effect of elevated CO_2 levels against yield depression by ozone. At present CO_2 levels, ozone at 57 nl l^{-1} depressed tuber yield by 9% compared with ambient O_3 (22.2 nl l^{-1}), whereas no ozone effect was observed at elevated CO_2. However, because of the large variation between individual sites, no overall statistically significant interaction was detected.

Conclusions

A large number of studies have been conducted on the effects of O_3 in combination with other gaseous pollutants, but the information obtained in many of these studies is very limited in the context of extrapolating to the real world, because of the unrealistic exposure conditions used. The pollution climate in many parts of the world has changed during the past decades as, for example, concentrations of "classical" air pollutants such as SO_2 have considerably declined. Future assessments of the effects of pollutant mixtures have to consider the ongoing changes in the global climate such as rising levels of CO_2. It is clear that the effects of O_3 on vegetation will be modified to some degree by global change components such as CO_2, but the magnitude of these changes and the mode of interactions are uncertain. However, recent research suggests that there is no consistent interaction between O_3 and CO_2 on plants. Although evidence is accumulating that elevated CO_2 may reduce the adverse effects of O_3 on plant growth and productivity, there are still large uncertainties to extrapolate the recent findings to plant responses under future changes in atmospheric compositions. Further research is needed to understand the complexity of multiple stress interactions involved in the modification of plant responses to predicted changes in climate and atmosphere.

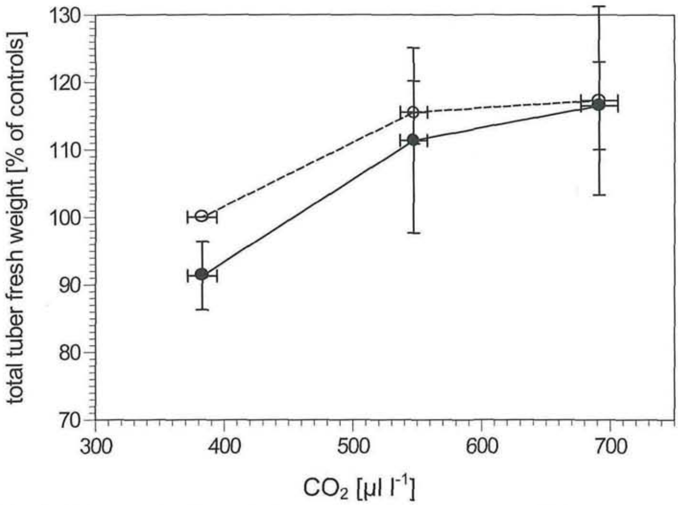

Fig. 2. Tuber yield of potato (*Solanum tuberosum* L. cv. Bintje) as affected by CO_2 and O_3 (data compiled from CRAIGON & al. 2002, including 6 different OTC experiments at 3 European sites). Open symbols: ambient O_3 (8 hr mean = 22.2 nl l^{-1}); closed symbols: high O_3 (8 hr mean = 57.0 nl l^{-1}). PCO_2: < 0.001; PO_3: n.s. (0.226); PCO_2xO_3: n.s. (0.675).

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