

## Chapter 24

### State of science and gaps in our knowledge in relation to air pollution

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#### Abstract

The IUFRO Research Group 7.04.00 “Impacts of Air Pollutants on Forest Ecosystems” in 1998 adopted, as one of its outputs from biennial international meetings, production of a series of general statements [Percy, et al., 1999, Water Air Soil Pollut. 116, 443–448] on the state of science from each of its Working Parties (WP). These discipline-oriented WP have continued to evolve in focus in tune with emerging issues and overall international research direction. The second IUFRO 7.04.00 report in this series emanating from concurrent sessions held during the 20th International Meeting for Specialists in Effects of Air Pollution on Forest Ecosystems “Air Pollution, Global Change and Forests in the New Millennium” follows.

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## 1. Diagnosis, monitoring and evaluation

### 1.1. State of science

Ozone ( $O_3$ ) continues to be of major concern in the field of air pollution effects on forest ecosystems. The need for adequate mapping of risks, identification and monitoring of symptoms, evaluation of effects and further research in this field were formerly mentioned as high priority areas (Percy et al., 1999) and were actually addressed in the meeting. Progress in mapping potential  $O_3$  risks was presented, suggesting that effects-oriented monitoring programs could take advantage by preliminary identification of target areas. This is thought to also be a step ahead in orienting the research toward more politically understandable end-points. Identification, confirmation and monitoring of  $O_3$  symptoms were reported for both southern Europe (Lombardy, Northern Italy) and North America (Great Lakes States, USA). In southern Europe, the changes of species assemblage along with altitudinal gradients, prevent any clear relationship with  $O_3$  exposure being identified. However, investigations carried out in the US provide convincing results that symptoms on native tree species correlate well with  $O_3$  exposure indices.

These findings can obviously provide further advantages when used to validate risk maps. Besides symptoms, effects on tree performance are of obvious interest. In this respect, novel results were provided for beech and, to a lesser extent, Norway spruce growing in permanent monitoring plots in Switzerland. After removing the effects of concurrent factors,  $O_3$  was reported to explain a considerable part of the variance in shoot growth for beech. Together with field surveys and investigations, the experimental approach remains important, especially to clarify what could be the effects of pollutants under specific conditions and/or to provide modellers with data that can be helpful when attempting to upscale the results of field measurements. In particular, competition was reported as an important factor to take into account when the response at the forest ecosystem level is to be investigated. Experimental results presented at the meeting actually indicate that competition is an important factor to take into account when attempting to evaluate the impact of  $O_3$  on tree growth.

Together with  $O_3$ , exceedance of critical loads for acidity and nitrogen remains a high priority for today's air pollution researchers. Findings of increases in tree mortality and nitrogen content (both in humus layer and needles) and lowering of other nutrients in areas where critical loads are exceeded were reported for Norway spruce.

Additional investigations addressed different forests and air pollution issues. The effects of bauxite mining on different habitats were reported for India, where an important concern is placed on the need to address the social aspects related to the evaluation of air pollution effects on forests.

Following a monitoring approach widely adopted in Europe, a variety of measurements (deposition, air chemistry, foliage chemistry, tree condition, needle wax) was presented from Polish national parks.

### **1.2. Knowledge gaps**

The role of scientists in existing monitoring activity, the value of critical levels/loads approach, the need for the research and the social aspects to be considered in, and outside, the developing countries were among the major discussion issues. Monitoring activity in the field of air pollution effects on the forest ecosystem is currently carried out through programs that, in some cases, are subjected to strong political control. Although policy is necessarily involved when setting priorities, identification of adequate methods of investigation and interpretation of results should be carried out by the scientific community. Unfortunately, this is not always the case, partly because communication and cooperation between scientists still need improvement and partly because the requirements that science may have in terms of quality of results and robustness of evidence may be problematic for politicians. At the end, however, there is a clear need to strengthen the role of scientists.

Aside from wide acceptance as operational tools, different settings of critical levels and loads are obvious between Europe and North America and this is a field where closer cooperation is needed. Here, a further problem is created by the need for definitions of exposure indices to be easily understood by many categories of users, within which politicians play a key role. Besides debating the value of a threshold against one another, modelers and ecologists should work together.

Stability and integrity of wilderness areas are of global interest and their monitoring is important. However, monitoring could be difficult in these areas because of a number of constraints, including costs and operational difficulties. Therefore, adequate investigation techniques should be proposed. Investigations into the effects of air pollution on forests can be difficult in developing countries, mostly because of financial constraints. In addition, there could be some reluctance to support studies about air pollution effects on forests in those places where air pollution is associated with some form of economical development. However, there is evidence that the contribution of developing countries to global air pollution will increase in the next decades (Fowler et al., 1999) and thus it is important to deal with the above problems, especially given that information gaps are much higher there.

From a different point of view, consideration about social aspects related to air pollution effects on forests is also relevant for developed countries. As was pointed out, demographic changes, population movements, increases in urban areas and mobility, and a comprehensive reshaping of needs and work access

will ultimately result in both changes in air pollution and demand for environmental quality. There is certainly a considerable need to explore the role of concurrent factors in determining the effects of a given pollutant. However, experiments and investigations in this field are scarce, and much needed.

Although investigations concerning O<sub>3</sub> effects on forests are well underway, a number of gaps, needs and improvement areas were identified. The role of scientists in designing and implementing monitoring programs is often frustrated by the need for quick and sometimes prepackaged answers suggested by politicians. To strengthen the role of scientists in existing programs, communication and cooperative meetings should be encouraged. On the other hand, researchers should take more responsibility, be more understandable and more willing to draw conclusions when possible. Strengthening the role of scientists will be beneficial for the credibility of monitoring programs, and help avoid biased interpretation of the monitoring results. Despite steady improvements in communication tools over the past years, communication between scientists remains an area where substantial progress has to be made. Benefits accruing will include increased research opportunities worldwide and better harmonization of methods. Thus, communication between scientists continues to be an important area of development in many different respects.

The critical loads approach, coupled with adequate mapping of exposures, can be of considerable help in identifying areas where forests may be at risk due to air pollution. Adequate, preferably low-cost, and easy-to-run investigation techniques (e.g., passive samplers for O<sub>3</sub>, bioindicators, . . .) should be identified, tested and disseminated for applicability in wilderness areas. Together with investigation techniques, care should be devoted to select an appropriate design for the field studies. Upscaling is increasingly important as site-specific data often have little meaning for policy makers. However, upscaling needs adequate models and data. Although long-term monitoring programs can provide much basic information, the experimental approach is important to clarify specific questions about the response of trees. Monitoring and experiments, especially conducted at large scale, should not be alternatives, but complementary parts. Proper experiments should be carried out to have adequate evaluation of the effects of factors such as competition on the responsiveness of forests to pollutants.

Although there are many questions to be solved, studies about air pollution effects on forests are widely carried out in developed countries. At the same time, the need for such studies is dramatically increasing in many countries currently under rapid development, where the resources to be devoted to such studies are limited. As the development of these countries is of global interest, a major challenge for the future will be to try and find some way to support scientists from these countries. The easiest way to do this, once again, is through improved communication, ensuring they are well informed on the

progress made in this field. Stronger support through cooperation is advisable and should be encouraged.

## **2. Mechanisms of action and indicator development**

### **2.1. State of science**

Presentations focused on four main topics: molecular mechanisms involved in O<sub>3</sub> injury, ecophysiological responses to long-term CO<sub>2</sub>–O<sub>3</sub> interactions, modelling O<sub>3</sub> effects on gas exchange, and bioindication by N/P dynamics or wood anatomy. By using marker genes, it has been determined that O<sub>3</sub>-, pathogen-, and wound-induced expression of both salicylic acid- and jasmonic acid-regulated defense genes, was attenuated in the O<sub>3</sub>-sensitive hybrid clone. Cell death in the tolerant clone was caused by induction of a salicylic acid-dependent programmed cell-death pathway (a hypersensitive response), while cell death in the sensitive clone was likely to be caused by the lack of a sufficient level of antioxidant defences.

Gas exchange and water relations were the main parameters examined under elevated CO<sub>2</sub> and O<sub>3</sub>. Carbon dioxide mitigated the negative effects induced by O<sub>3</sub>, but there were indications suggesting some species and some genotypes within species may have their sensitivity changed by elevated CO<sub>2</sub> and by presence of aboveground competition. A new effect of CO<sub>2</sub> and O<sub>3</sub> on leaf area development was also identified; depending on the developmental stage of the leaf, the effect of both O<sub>3</sub> and CO<sub>2</sub> can either inhibit or stimulate the foliar distension rate.

Findings on nitrogen and phosphorus dynamics stressed once more the importance of climatic factors in determining plant response to elevated O<sub>3</sub> and CO<sub>2</sub>. Wood production under elevated pollution was also examined, in terms of both quantity and quality.

Finally, two approaches for modelling O<sub>3</sub> uptake during different episodes were developed. In aspen, O<sub>3</sub>-induced growth responses were simulated using a functional and structural tree growth model with built-in, process-based photosynthesis routines for sun and shade leaves. In another species and site-specific model it was possible to calculate stomatal O<sub>3</sub> uptake in ponderosa pine on the basis of episodic micrometeorological data only.

### **2.2. Knowledge gaps**

Ozone degrades to Reactive Oxygen Species (ROS), such as superoxide, hydroxyl radicals and hydrogen peroxide in the plant cell wall, and elicits active ROS production in plant cells, similar to the oxidative burst in plant–pathogen interactions. The role of salicylic and jasmonic acids as mediators/modulators

of ROS-induced plant responses has been elucidated by different research groups and by using different plant species (*Arabidopsis*, *Betula pendula*, and a hybrid poplar). Such results indicate a strong requirement for the extension of the molecular approach to other tree species, in order to provide information on the genetic and mechanistic basis of natural variation in O<sub>3</sub> sensitivity.

In terms of scaling up from molecules to ecosystems, gaps still remain with special reference to root physiology, plant competition, and progeny fitness. A new approach has to be developed to increase the scale of investigation. Good perspectives are implied in modelling, as a tool to coordinate and integrate experimental data, even if application might be difficult, as models are usually species- and site-specific. At any rate, models may help in defining the key processes and the key parameters to be investigated. Ozone flux entering the leaves appears to be more promising than an AOT40 approach, as it correlates better to physiological parameters. Further, it appears to be of special interest to determine how CO<sub>2</sub> can influence the detoxification processes in an increasing oxidizing environment.

On the more technical side, today there are different working tools. Among these, Free-Air Pollutant Exposure Systems (FACE) experiments are the most promising, but there was general agreement on the continued usefulness of conventional approaches such as OTC, field plots, or climate chambers to investigate specific processes.

The restructuring of this WP toward mechanisms of action and indicator development has opened new horizons and has provided new objectives for our biochemical and physiological research. This enables our group to adopt an explanatory and mechanistic approach, following the principles that all good research should pursue, and to meet the needs of modern research, combining ecophysiology, molecular biology, and modelling. In short, becoming more inter- and multidisciplinary will enable us to be more efficient in our research task of 'Mechanisms of action and indicator development'.

### **3. Atmospheric deposition, soils and biogeochemistry**

#### ***3.1. State of science***

The importance of dry deposition of gases and particles in the Mediterranean climate of southern California was emphasized. Dry deposition can provide as much as 90–95% of all atmospherically deposited nitrogen (N) to California forests and other ecosystems. Long-term elevated levels of N deposition change nutritional status of soils and affect forest and other ecosystems. For example, the coastal sage scrub community in southern California has expe-

rienced significant shifts in vegetation composition that may be attributed to these changes.

Nitrification is the key process leading to elevated N losses in the San Bernardino Mountains of southern California that experience long-term elevated levels of N deposition. As a result, streamwater is highly contaminated with nitrate at the highest levels for the undisturbed wildland watersheds in North America. At the high N deposition forest sites, after 3 years of N fertilization, growth of both pine and oak trees increased. It is suggested that due to the highly open nature of N cycling in the Mediterranean climate, stage 3 of the N saturation hypothesis (forest decline or reduced NPP) may be difficult to achieve in these forests.

A 4-year study on responses of ponderosa pine seedlings to elevated levels of CO<sub>2</sub> and O<sub>3</sub> is being performed in the outdoor exposure chambers. After two seasons of exposures, shoot growth of pines significantly increased at elevated levels of CO<sub>2</sub>, especially at the low O<sub>3</sub> concentrations. When completed, this study will provide information on interactive effects of CO<sub>2</sub> and O<sub>3</sub> on biogeochemical cycles of pine/litter/soil mesocosm.

Ponderosa pine seedlings were grown with blue wild-rye grass to determine if the presence of natural competitors alters responses of pines to O<sub>3</sub>. Grass presence significantly reduced total pine mass by nearly 50% after 3 years of O<sub>3</sub> exposure, but O<sub>3</sub> alone had no significant effects on pine growth. Competition for soil N, moisture, and light were the primary factors driving the responses of pines to grass competition.

Model ecosystems of beech and spruce seedlings were exposed to ambient and elevated levels of CO<sub>2</sub> and low and high wet N deposition for 4 years in open-top chambers. CO<sub>2</sub> effects on nutrient cycle and water relations were clearly species and soil dependent. Elevated CO<sub>2</sub> increased both growth and N-use efficiency of spruce on acidic loam and the calcareous sand, but in beech only on the nutrient-rich calcareous soils. This study suggested that elevated CO<sub>2</sub> increased N immobilization in soil, therefore, growth of forests may be restricted at the future CO<sub>2</sub>-rich environment.

Short-term changes in dynamics of aspen and paper birch leaf decomposition due to elevated concentrations of CO<sub>2</sub> and O<sub>3</sub> were assessed in a litter bag experiment at the Aspen FACE study. This study revealed that effects of elevated CO<sub>2</sub> + O<sub>3</sub> levels were complex and could not be predicted from decay rates under elevated CO<sub>2</sub> or O<sub>3</sub> applied alone.

### 3.2. Knowledge gaps

Examples of research priorities stemming from discussions on knowledge gaps include the following: additional work on the effects of gaseous pollutants (O<sub>3</sub>, CO<sub>2</sub> or HNO<sub>3</sub> vapor) on biogeochemical cycles and on the role of soil systems

in responses of ecosystems to multiple stresses (air pollutants and other abiotic and biotic stressors) should be undertaken. Of course, effects of air pollution deposition on C sequestration and on the role of different forms of N deposition inputs on biodiversity changes as well as C sequestration need to be better understood.

The effects of deposition and biogeochemical changes in forests on water resources remain a priority in which relatively little work is concentrated. Development and evaluation of critical loads of N and S deposition for various ecosystems (taking into consideration complexities of systems in different geographical and ecological settings, effects of O<sub>3</sub> and CO<sub>2</sub>, etc.) should be advanced.

Of major importance in the policy-setting framework is the development and use of models (linking atmospheric, plant and soil components) for evaluation of ecological risks from atmospheric deposition to plants, forest stands and landscapes. This must implicitly rely upon the development and use of new research approaches, such as large-scale use of passive samplers for air pollutants, air pollution gradient studies, etc.

#### **4. Influence of air pollution and climate change on genetics, adaptation and succession**

##### ***4.1. State of science***

Presentations in this concurrent session focused on two main topics. The first topic centered on the genetic response of sensitive and tolerant clones of broad-leaved trees (aspen, paper birch and silver birch) to elevated levels of O<sub>3</sub> and CO<sub>2</sub>. Investigated responses were stomatal conductance, stomatal density, photosynthetic rate, rubisco activity, and epicuticular wax composition. Clear evidence of the impact of O<sub>3</sub> and of the interactive effect of O<sub>3</sub> and CO<sub>2</sub> was shown. The second main topic corresponded to the selection effects and differences in genetic structure of natural and semi-natural populations of Norway spruce, European silver fir, European beech and aspen exposed to O<sub>3</sub>, heavy metals, or salts. Simulation of effects of global warming of climate on genetic structure of forest trees populations was also presented.

Individual case studies have shown clear evidence of large differences in response of various clones (genotypes) of silver birch, paper birch and aspen to elevated O<sub>3</sub> and CO<sub>2</sub> in terms of stomatal conductance, stomatal density, and also in the overall physiology of trees as measured by photosynthetic rate and rubisco activity. The influence of the combined effects of O<sub>3</sub> and CO<sub>2</sub> on epicuticular wax composition, structure, and relative amount of different wax compounds has also shown the negative impact of these gases on sensitive

genotypes in O<sub>3</sub> gradient and FACE studies. The observation could have important implications for host-herbivore and pathogen interactions. Ozone impact on the competitive ability and fitness (mortality rate and volume relative growth) of clones of aspen sensitive and tolerant to O<sub>3</sub> is providing exciting new data demonstrating the selection for O<sub>3</sub> tolerance in aspen.

A case study on differences in genetic structure of groups of Norway spruce and European beech, both sensitive and tolerant, to industrial air pollution has demonstrated opposing trends for Norway spruce and European beech in terms of their isoenzyme variation. Simulation of climate warming and the influence of this phenomenon on genetic structure indicate that in populations of *Picea abies* trees from warmer conditions, a higher diversity occurs. However, different types of isoenzyme markers would be expected to produce different results. The influence of O<sub>3</sub> on genetic structure of the progeny from tolerant and sensitive *Picea abies* trees has shown clearly that selection processes are acting strongly on the embryos of sensitive trees.

The usefulness of new molecular markers (untranslated region of ribosomal protein gene) for heavy metal and salt stress in *Picea abies* was demonstrated.

#### 4.2. Knowledge gaps

There is very little information on the dynamics and trends on changes connected to selection processes, and on the genetic structure of populations affected by air and soil pollution. There is an urgent need for more information about competition between genotypes in natural and artificial populations while exposed to various stress factors. There are also knowledge gaps with respect to adaptive strategies of particular forest tree species, as well as populations of these species, to different stress factors such as air and soil pollution. Such data are required in the case of elevated O<sub>3</sub>, CO<sub>2</sub>, and climate warming, to set policy for the protection of tree germplasm.

Little information is available on which isoenzymatic loci are diagnostic and could be used as good and reliable markers for selection/changes in genetic parameters for various tree species. We still need additional molecular markers, isoenzymatic, and DNA as indicators of genetic response to stress factors. We also need better linkage between the markers and physiology of plants under stress. For preservation of *in situ* and *ex situ* genetic diversity and genetic "richness" of forest tree populations as a necessary base for ability to adaptive processes, there is need for a monitoring study of tolerant stress factor populations and also "natural" ones.

In particular, there is insufficient information on the correlation between such phenotypic traits as growth, fertility, volume production, tolerance and sensitivity and molecular markers (isoenzymes and DNA). Interactions be-

tween different abiotic and biotic environmental stress factors also need to be further investigated.

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