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Commentary

Advances of air pollution science: From forest decline to multiple-stress effects on forest ecosystem services☆

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Interactions between air pollution and climate change effects on forest services demand long-term research approaches that integrate multi-factorial field experiments, monitoring and modeling.

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ABSTRACT

Over the past 20 years, the focus of forest science on air pollution has moved from forest decline to a holistic framework of forest health, and from the effects on forest production to the ecosystem services provided by forest ecosystems. Hence, future research should focus on the interacting factorial impacts and resulting antagonistic and synergistic responses of forest trees and ecosystems. The synergistic effects of air pollution and climatic changes, in particular elevated ozone, altered nitrogen, carbon and water availability, must be key issues for research. Present evidence suggests air pollution will become increasingly harmful to forests under climate change, which requires integration amongst various stressors (abiotic and biotic factors, including competition, parasites and fire), effects on forest services (production, biodiversity protection, soil protection, sustained water balance, socio-economical relevance) and assessment approaches (research, monitoring, modeling) to be fostered.

1. Introduction

The 23rd Conference for Specialists in Air Pollution and Climate Change Effects on Forest Ecosystems hosted by the International Union of Forest Research Organizations (IUFRO) and focused on "Air Pollution and Climate Change at Contrasting Altitude and Latitude" was held during September 7–12, 2008, in Murten, Switzerland (Schaub et al., 2010). This event continued the tradition of biannual meetings of the IUFRO Research Group 7.01.00, entitled "Impacts of Air Pollution and Climate Change on Forest Ecosystems". Research trends, new findings and future research needs emerging from the conference are summarized in this commentary. Included is

☆ This special section of Environmental Pollution is dedicated to two outstanding and esteemed colleagues, who have passed away during the year past the IUFRO conference in Murten, addressed here. On 24 October 2008, Prof. David Karnosky of the Michigan Technological University, a friend and longstanding colleague of the IUFRO community suddenly passed away. Dave changed the air pollution science and introduced exposure of trees to air pollution under realistic field conditions. Dave's wide vision, leadership, scientific competence and consensus-building skills resulted in a great success of the Aspen FACE study in Wisconsin, the only FACE site where scientists studied the combined impact of carbon dioxide and ozone on forest ecosystems. On 18 August 2009, Prof. Heinrich Sandermann of the Helmholtz Zentrum München/Germany (formerly GSF Research Centre) passed away after serious illness. Heinrich was known to the IUFRO community for his excellent scientific contributions on air pollution impact on vegetation, giving innovative impulses and stimulating encouragement for research towards mechanistic understanding of plant response. A breakthrough was his clarification of the primary processes initiated by ozone at the molecular and biochemical level. His achievements and vision will continue to give guidance to air pollution and global change-related research. With Dave Karnosky and Heinrich Sandermann, we have lost not only two brilliant colleagues, but also good friends. We will miss their friendly and humorous personalities – their memory and inspiration will continue to live on.

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a comparison with the 14th conference of the same series, “Air Pollution and Forest Decline”, that was held in Interlaken, Switzerland, 20 years ago (October 2–8, 1988).

2. Progress in research topics

Over the past 20 years, the focus of forest science on air pollution has moved from forest decline to a holistic framework of forest health, and from effects on forest production to ecosystem services such as sustained biodiversity, soil protection, water balance and socio-economical benefits. Dominating topics of presentations 20 years ago were forest decline, air pollution, and tropospheric ozone, followed by silviculture, acid rain, nitrogen deposition and others (Fig. 1). In 2008, ozone and nitrogen deposition received increased awareness, and acid load still drew attention in spite of the substantial decrease in its research emphasis in Europe and North America over the past 20 years (Bytnerowicz et al., 2007). In 2008, a new emphasis incorporates the effects of elevated CO_2, climate change and below ground processes. Finally, aspects of forest genetics were another research thrust with renewed interest in 2008 in comparison to its marginal coverage in 1988.

Compared to 20 years ago, when research focused on one-factor experiments, multiple-stressor effects are key issues of present forest ecosystem research, which include combined effects from seasonal variability of air pollution, elevated CO_2, and altered nutrient and water availability. This change in science is an apparent consequence of research evidence about antagonistic and synergistic factorial pathways that have accumulated since the studies on forest decline during the 1980s. Unraveling the mechanistic grounds of interactions between pollution and climate, and of the variability incited in tree and ecosystem response, demarcates the key issues of the Murten conference in 2008 towards consolidating risk assessment of forest ecosystems in the future.

3. Key conclusions and further research needs from the 2008 conference

Tropospheric ozone (O_3), as a phytotoxic pollutant and an agent of climate change, is still considered to be the most important air pollutant for forests. While climate change scenarios predict increasing frequency of drought episodes (reducing O_3 risk to vegetation), increasing O_3 concentrations will affect areas with sufficient water availability even more (Sitch et al., 2007) and O_3 exposure will impair stomatal regulation and thus the control of tree water loss (Grulke, 2010). Interactions of O_3, biotic infections, climatic and edaphic factors are still poorly understood. More long-term investigations on these interactions are needed while applying multi-factorial experimental set ups under natural or close to natural conditions for establishing O_3 uptake (Nunn et al., 2010) and defense (Matyssek et al., 2010) and hence adverse effects on forest trees and stands. Untangling the mechanisms of plant sensitivity and simplifying them into practicable indices and proxies for modeling are the main challenges of present O_3 risk assessment (Paoletti et al., 2008). Ozone effects on biodiversity also demand for future attention in research. Free-air O_3 exposure experiments suggest that pioneer trees may be more sensitive than climax species, although the variability of O_3 sensitivity between genotypes of one species may be larger than among different species (Matyssek et al., 2010). While synchronized networks of towers measuring CO_2 fluxes and N deposition as well as climatic variables are available (e.g. Magnani et al., 2007; de Vries et al., 2008), a similar network for monitoring long-term O_3 fluxes is lacking. Most often, information on ambient O_3 levels in the field is lacking as well as detailed knowledge on response indicators, thus precluding analysis and modeling of O_3 impact on C and water balance at the landscape level.

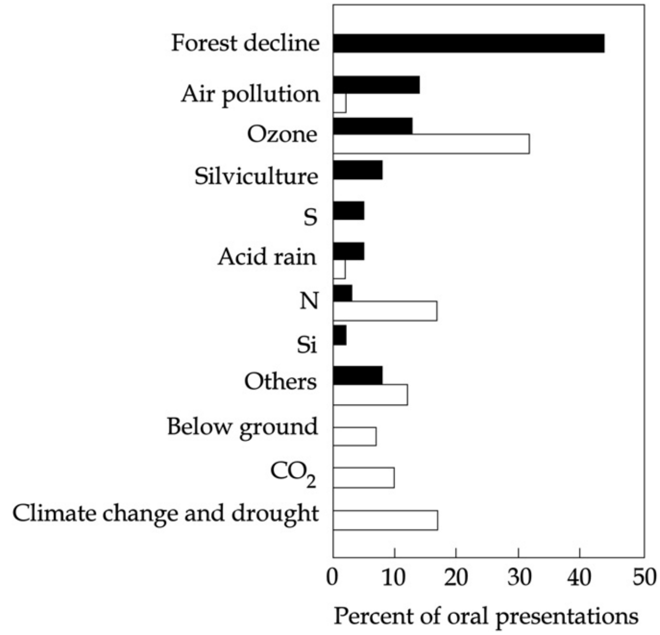

Fig. 1. A comparison on the research topics presented at the IUFRO conferences on “Impacts of Air Pollution and Climate Change on Forest Ecosystems” in 1998 (Interlaken, black bars) and in 2008 (Murten, white bars).

Recent findings demonstrate that **elevated CO_2** is unlikely to cause a sustainable increase of C storage in forest biomass, although it may enhance C turnover (Körner, 2006). However, the C cycle is nested in a multitude of feedback loops and influenced by further factors such as nutrient and water availability (Leuzinger and Körner, 2007). Those results demonstrate the importance of simultaneous investigations of the carbon, water and nutrient cycles under natural forest conditions. In addition, species differ in their responsiveness to CO_2, which induces biodiversity effects that may become more important in the long run than elevated-CO_2 effects on leaf gas exchange (Keel et al., 2007). Also, Uddling et al. (2010) suggest that model projections of large CO_2-induced reductions in stomatal conductance alleviating the adverse effect of rising tropospheric O_3 may not be reasonable for northern hardwood forests. The oversimplification of the effect of single environmental effects, measured over short time periods, may lead to wrong conclusions about the combined air pollution and climate change affects on forest ecosystems.

Nitrogen (N) deposition and effects on forest ecosystems are still a major research topic. Excessive N input may interact with other pollutants and climatic factors and induce adverse effects such as acidification, eutrophication, reduced biodiversity (Clark and Tilman, 2008), increased pest attacks and visible O_3 injury (Grulke, 2010) as well as nutrient imbalances (Braun et al., 2010). In turn, N-induced deficiencies in potassium and phosphorous increase drought damage and inhibit tree growth, which leads to conclude that growth increase due to N deposition is not beneficial to trees and forest ecosystems (Braun et al., 2010). Increased drought sensitivity may be enhanced by an increased shoot–root ratio or by decreased mycorrhizal activity. Promising is the use of tree-ring $\delta^{15}N$ to detect effects of past precipitation and temperature regimes, provided the effects of NO_x emissions can be separated from climatic effects (Savard, 2010).

At present, there are well established relationships between the exceedance of **critical loads** and ecosystem degradation.

Nevertheless, ecological interactions between critical loads and other environmental factors such as the impact of increased concentrations of CO_2 and O_3, insects, pathogens, fire, drought, flooding, wind, and extreme temperatures as well as ecosystem management practices, are still poorly understood (McNulty and Boggs, 2010). There is a need to develop dynamic models for calculating critical loads, i.e. addressing changing levels of deposition and its effects, to define suitable indicators and damage thresholds, and to evaluate the combination of critical loads within the context of other environmental stresses.

Biodiversity effects of air pollutants and climatic factors suggest that a major future challenge is the better understanding of how genes determine physiological plasticity, adaptation and survival of tree populations. Appropriate methods of monitoring genetic traits, and the functional characterization of transcripts at a large scale are available. Studies on quantitative trait loci (QTL) in tree species are in progress (e.g. Rae et al., 2007). The increase of knowledge in the fields of genomics and transcriptomics is evident but generally, information on the genomes of tree species as compared to other plant species is still fragmentary. Filling these gaps in the frame of environmental genetics is a challenge and a determinant for future research.

With respect to **integrated effects of multiple stressors**, there is sound evidence that the focus of future research has to be on interacting effects and not on one single environment parameter (as a potential stressor) due to antagonistic and synergistic reactions of forest trees and ecosystem compartments (Grulke, 2010).

Monitoring is not only essential to document current status and changes in forest health under changing climate but also of great importance to political decision regarding declining forest condition issues. This includes a variety of flanking effects, from implications on biogeochemical cycles at the timberline (e.g. Wieser et al., 2009) to the replacement of species (e.g. Dobbertin et al., 2010) and trade-offs concerning fitness parameters (e.g. Seifert and Müller-Starck, 2009). Interactive effects of air pollution and climate change on forest ecosystems demand long-term monitoring. Conclusions from a series of excellent projects, integrating experimentation and monitoring at Californian field sites, indicate humans, drought and air pollution to perturb ecosystem more rapidly and distinctly than do increasing CO_2 and temperature (Grulke, 2010). Short time series over roughly 10 years could easily be misinterpreted in the context of global climate change. Only long-term measurements will allow us to accurately detect how ecosystems respond to climate change, and whether there are measurable effects of nitrogen deposition and pollutant fluxes.

The issue of **risk assessment** is gaining increasing interest especially in the light of the current focus on climate impacts on ecosystems functions. A thorough understanding of the single processes and the interactions between processes is essential to understand and model current and future mechanisms, and to assess levels and areas of risk. Both statistical models and process-based models allow for integration of the knowledge acquired from detailed experimental data and monitoring data. A major issue is to include both air pollution and climate change and their impacts on ecosystems, and to adequately support those data by both field observations and experimentation.

4. Conclusions and perspectives

Air pollution effects on forest ecosystems have achieved considerable advances during the past 20 years, although major uncertainties remain in our ability to assess air pollution impacts on forests under current site conditions and in particular regarding effects of air pollution as a component of climate change. Overall, current knowledge suggests predicted pollution impacts to become more deleterious to vegetation due to climate change, although the complexity of involved feedbacks still represent a research challenge. The cause–effect relationships of multi-factorial anthropogenic and natural interactions with respect to biodiversity, water, nutrient and carbon cycling, and related ecosystem functions can only be resolved through interdisciplinary efforts. Experiments that lack a natural atmosphere – plant – soil linkage are fundamentally unsuitable for making ecosystem scale inferences. Methodologically, the door is wide open for employing genetic information as an indicator for ecosystem processes which are relevant for adaptation and survival of tree populations. Furthermore, genome based research for carbon sequestration in terrestrial ecosystems is one of the tools which can contribute efficiently to the solution of problems in a global dimension. Holistic approaches are available for upscaling information from laboratory to the field, and from gene to the landscape. An important improvement in our understanding might be obtained by the combination of long-term multi-factorial experiments with ecosystem-level monitoring, and subsequent integrative ecosystem modeling. Long-term monitoring of ecosystem response to climate change and air pollution within trans-continental research efforts will lead to a global understanding, as ecological and functional feedbacks across climate, biogeochemical and land use changes will dominate future forest ecosystem responses and global resource fluxes. A conclusive and quantitative understanding of multiple, functional feedbacks must be the objective of future research.

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