

Chapter 25

Air pollution and global change impacts on forest ecosystems: Monitoring and research needs

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Abstract

The start of the 21st century brings an increasing public awareness of environmental issues worldwide. In this book, we have attempted to present the current state of knowledge about CO₂ effects and related global warming on forest productivity and ecosystem function and to discuss research needs in that regard. In addition, we have discussed other air pollutants including O₃, nitrogen and sulfur compounds, and heavy metals. The status of those pollutants globally and some representative effects on forest trees and forest ecosystems have been presented. Certainly, there remains much to do in monitoring air pollutants, particularly in rural and forested areas. For example, very little is known about expanding pollutant loading in forest areas of developed countries or across both urban and forest areas in developing countries where the need to industrialize is generally outweighing the resources to control pollutant emissions. While great strides have been made in the past few decades to decrease acidic deposition in North America and Europe, there remain extensive areas of the world's forests being impacted by acidic deposition. Similarly, large areas (25%) of the world's forests are currently exposed to elevated levels of O₃ and this is projected to rise to fully 50% of the world's forests by the year 2100. Thus, research is needed to

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document pollutant effects and to reduce uncertainties about forest productivity and forest ecosystem responses worldwide in the next century. In this chapter, we summarize the eight major research and monitoring needs for the investigation into air pollutant impacts on forests worldwide.

1. Introduction

Air pollution and climate change are two key factors threatening forest health and sustainability. Considerable scientific effort, mainly in northern hemisphere countries, has been devoted to the enhancement of our understanding of forest responses to global change at the process, organ, system, stand and ecosystem levels. Forest ecosystems around the world are being exposed to increasing levels of atmospheric CO₂ and changing climates. In addition continental and regional scale air pollutants, such as O₃ and acidic deposition, and numerous forms of S and N are impacting large sections of the world's forests.

Fowler et al. (1999) have calculated areas of forests where July peak surface O₃ concentrations have exceeded 60 ppb. In 1950, this area was largely restricted to the temperate latitude forests. By 1990, 25% of the forests were exposed to > 60 ppb July peak O₃. In 2100, fully 49.8% of the world's forests (17.0 million km²) will likewise be exposed.

Fowler et al. (1999) have also estimated the area of global forests at risk from acidification (> 2 keq H⁺ ha⁻¹ yr⁻¹ as S). They predicted a 21-fold increase in area of global forests at risk between 1985 (0.28 million km²) and 2050 (5.9 million km²), with the majority of the increase in sub-tropical and tropical forest regions.

In summary, forest trees and ecosystems are facing combinations of gradually increasing CO₂, warming temperatures, and changing seasonal phenology, often in concert with elevated air pollution (Houghton et al., 2001). Unless there is a strong downturn in global population growth and industrialization, forests will continue to be exposed to a deteriorating atmospheric environment. Areas of forests at risk from O₃, S, N and acidification are expanding under current economic and social trends. Modeling of future S and N scenarios for North America and Europe indicates that although the driver of acidification is changing (molar ratios in rain are now almost equal for N and S, whereas S in the past dominated for many decades), acidification potential in many areas remains high (<http://nadp.sws.uiuc.edu>).

The goal of this book has been to explore the impacts of air pollution and climate change on forests and forest ecosystems around the world. Trends in the major air pollutant types and their generalized effects on forests are summarized here in Table 1. In addition, we discuss the most outstanding monitoring and research questions still needing to be addressed by the international scientific community and list them in Table 2.

Table 1. The occurrence of major air pollutants are changing. In this table, we describe how these pollutants are changing and what is known about their impacts on forest ecosystems

Pollutant	Distribution and change	Forest effects	See discussion in chapters
CO ₂	Increasing globally	<ul style="list-style-type: none"> • Short-term growth and productivity increase; long-term effects still undetermined • Implicated in global warming and predicted to cause massive shifts of species ranges 	1–3, 19, 21–24
O ₃	Global increases in O ₃ and its precursors with largest increases coming in developing countries	<ul style="list-style-type: none"> • Growth and yield losses in sensitive species and impacts on relative fitness and on community dynamics • Predisposition of forest trees to insect and diseases 	1, 2, 4–13, 19, 20, 22–24
Nitrogen (N) (NO _x , NH ₃ , etc.)	Global increases, particularly in developing countries (especially India and China)	<ul style="list-style-type: none"> • Stimulation of growth and productivity in N-poor soils • N-saturation in some forests causing decline and in many streams, ponds, and lakes causing fish species shifts and extinction • Contributes to increases in O₃ 	1, 2, 14, 15, 21, 24
Sulfur (SO ₂ , SO _x , H ₂ S, etc.)	Stable globally with steady decreases in the past few decades in developed countries but increasing in several developing countries (especially India and China)	<ul style="list-style-type: none"> • Acidified soils in many parts of the world are difficult to mitigate 	1, 2, 14, 15, 21, 24
Heavy metals	Decreasing problem in developed countries, continued localized point-source problem in many developing countries and nations in transition	<ul style="list-style-type: none"> • Localized forest extinction and toxic soils which limit the ability to regenerate forests 	1, 2, 17, 18, 24

2. Monitoring needs

1. Air pollutant concentrations are changing rapidly and these changes need to be documented (Table 2). For example, until recently, it was thought that daytime global CO₂ concentrations were similar. However, research has shown that while a daytime background level of ~ 360 ppm is relatively common around the world today, there are large metropolitan areas such as Phoenix

Table 2. Important monitoring and research needs for the world's major air pollutants

Pollutant	Monitoring	Forest research ^a
CO ₂	<ul style="list-style-type: none"> • Continued background CO₂ monitoring and expanded CO₂ monitoring in urban areas • Continued temperature measurements around the world • Continued phenological studies of forest trees • Examine trees along range margins where global warming responses are first likely to occur 	<ul style="list-style-type: none"> • Effects of elevated CO₂ and global warming on: <ol style="list-style-type: none"> (a) Long-term growth and productivity (b) Ecosystem-level responses such as biogeochemistry and cycling of nutrients, water balance, etc. (c) Community dynamics and population changes (above- and below-ground) (d) Effectiveness in carbon sequestration by various methods of afforestation, reforestation, and agroforestry (e) Methods to increase carbon sequestration (amounts and duration of sequestration) • Interactions of elevated CO₂ with global warming, increased N deposition, or elevated O₃, etc. • Linking of FACE/FLUXNET networks to study C cycle
O ₃	<ul style="list-style-type: none"> • Increased monitoring forest areas around the world • Increased monitoring in urban and rural areas of developing countries • Examine relationship of forest health to O₃ or other pollutants • Increased use of passive samplers for forest areas for monitoring • Link Forest Health Monitoring to O₃ monitoring • Link Forest Health monitoring to GIS, GPS, etc., to allow eventual satellite imagery use in forest health characterization 	<ul style="list-style-type: none"> • Effects of elevated O₃ on stand, community, and ecosystem levels • Increased use of field techniques for ecosystem-level research such as FACE, O₃ gradients, and dendrochronology • Effects of elevated O₃, alone and in combination with other pollutants, on foliar symptoms and growth in developing countries • Increased understanding of why some trees or plants are sensitive to O₃ and some are not, facilitated by large scale gene expression studies • Effects of global change on volatile organic compound production • Effects of interacting O₃ and other pollutants

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(Idso et al., 2000), Baltimore (Hom et al., 2001), and Chicago (Grimmond et al., 2002) where daytime CO₂ concentrations can be > 100 ppm higher. It is worth noting as well that night-time concentrations may be > 100 ppm higher in non-urban areas where plants are a source, rather than a sink at night (Legge and Krupa, 1990).

Table 2. (Continued)

Pollutant	Monitoring	Forest research ^a
N	<ul style="list-style-type: none"> • N deposition in developed countries and especially in developing countries with rapidly expanding automobile traffic and industry (i.e., India, China, Nepal, Chile, and Mexico) • Long-term monitoring of acidified streams, ponds, and lakes • Long-distance (intercontinental) N transport and the effects of this transported N on O₃ formation 	<ul style="list-style-type: none"> • Effects of N additions in N-saturated or nearly N-saturated ecosystems • Effects of N additions to ecosystems experiencing other pollutants (i.e., CO₂, O₃, S, etc.) • Effectiveness of various N mitigation treatments on forest soils and waterways
S	<ul style="list-style-type: none"> • S deposition in countries in transition and in developing countries • Continued assessments of impacted forest ecosystems to ensure proper restoration 	<ul style="list-style-type: none"> • Methods to mitigate long-term sulfur inputs into soils and to restore sustainable forest ecosystems • Effects of SO₂ and sulfur deposition on forest trees in developing countries, particularly tropical countries where little air pollution effects research has been done.
Heavy Metals	<ul style="list-style-type: none"> • Continued monitoring near point sources of heavy metals 	<ul style="list-style-type: none"> • Mitigation and restoration of forest ecosystems devastated by heavy metal deposition

^aWhile we highly endorse research to reduce emissions or the precursors of all of these major pollutants, we focus here on major knowledge gaps or research needs for forest ecosystems.

Other primary pollutants, such as nitrogen oxides, volatile organic compounds and sulfur oxides are transformed in the atmosphere, in some cases very rapidly and their products subjected to long-range transport. For those pollutants, the majority of effects may be much farther downwind of the source. For example, there are many Class I wilderness areas in the US and Canada that are being exposed to high levels of O₃ (NPS, 2002). In developing countries such as India, Malaysia, China, and also countries in transition in eastern Europe, with rapidly expanding economies, growing industrialization, rising populations of concern in some cases and increasing traffic volume, expanded air pollution monitoring is needed in and around major cities and in forested areas to document trends in air pollution occurrences (Gupta et al., 2002; Kimmel et al., 2002). Continued monitoring of restoration progress in previously seriously impacted forest ecosystems (as in the Black Triangle in central Europe (Fanta, 1994, 1997; Karnosky, 1997) is needed to determine if mitigation approaches and decreased emissions are helping those disturbed ecosystems.

2. With respect to the most pervasive air pollutant affecting forests, we know that ambient O₃ concentrations are highly variable in space and time and exhibit a dynamic flux to plant canopies (Krupa et al., 2003). Therefore, continued and expanded monitoring is needed in developed countries to better document pollutant deposition in forested areas (Bytnerowicz et al., 2002, Bytnerowicz et al., 2003; Zimmerman et al., 2003). The more widespread use of passive samplers has clearly extended the area for which O₃ data are now available, at least in the form of a single period, integrated concentration (Krupa and Legge, 2000). The subsequent development of a Weibull probability model and the most recent meteorology integrated statistical model to predict hourly ambient O₃ concentrations from single weekly passive sampler data (Krupa et al., 2001; Krupa and Nosal, 2001; Krupa et al., 2003) have enhanced the utility of passive samplers and their continued development and use should be expanded to decrease the uncertainty regarding O₃ concentrations in rural forested areas.

3. Forest health monitoring continues to be used in both the USA (Smith, 2002; USDA Forest Service, 2003) and Europe (DeVries et al., 2000; ICP, 2002) in an attempt to quantify visible symptoms and crown vigor and to link those conditions, among other causes, to ambient air pollution. Regrettably, there is no universally accepted definition of forest health (Percy, 2002). However, in the context of forest response to air pollution, the sustaining of ecosystem structure and function is especially important because process-oriented and pattern-oriented considerations have been shown to underpin any definition of forest health. McLaughlin and Percy (1999) have accordingly defined forest ecosystem health as the capacity to supply and allocate water, nutrients and energy in ways that increase or maintain productivity while maintaining resistance to biotic and abiotic stresses. This definition fits quite well within new forest health concepts built around issues such as long-term sustainability, resilience, maintenance of structure and functions and multiple benefits and products (Kolb et al., 1994). Thus, expanded visions are needed for forest health monitoring (Percy and Ferretti, 2003). For example, expanded use of GIS (Geographic Information System), GPS (Geographic Positioning System) and other satellite-based systems, linked to the ground through ground truthing, could be useful in Forest Health Monitoring in the future.

Approaches commonly used to assess forest health are generally inadequate for evaluation of trends, for detection of future change, and for elucidation of the roles of natural and anthropogenic stressors. Integrated approaches linking process-oriented empirical studies with pattern-oriented monitoring along defined spatial variations in pollution using clonal plantations (Karnosky et al., 1999), genetically-screened tree pairs (Muller-Starck et al., 2000), ecological analogues (Krupa and Legge, 1998), and ecosystem-based research on essential cycles (FACE or other non-exposure chamber based techniques) with better characterization of physical and chemical environments are needed. In turn,

these will yield new approaches toward a statistically and conceptually sound monitoring system required if the interactive effects of global change (air pollution + climate change) on forest health and sustainability are to be understood in the 21st century. Long-term ecological research is essential to understand the status and trends in processes within forest ecosystems. Close linkages need to be made between atmospheric and ecological monitoring. For example, in the US, linking existing acidic deposition (NADP/NTN) and air quality (AIRs) monitoring networks with the Forest Health Monitoring program could yield some valuable insights into forest health.

4. Global warming, associated with greenhouse gas emission trapping of radiant energy near the earth's surface, has created concerns about species range shifts (Parmesan and Yohe, 2003; Alley et al., 2003; Bakkenes et al., 2002; Houghton et al., 2001; IPCC, 2001), extensive insect and disease outbreaks (Aber et al., 2001; Bale et al., 2002), forest fires and large-scale forest community changes. Extensive forest monitoring will need to be done to continue to document effects of elevated greenhouse gases and global warming on above-ground and belowground competitive interactions (McDonald et al., 2002; Poorter and Navas, 2003), canopy and soil community dynamics (Karnosky et al., 2001), and forest health (Percy and Ferretti, 2003). Continued monitoring of phenological gardens (Menzel and Fabian, 1999) and long-term studies along the edges of species ranges will be needed to document the rates and magnitude of climate change impacts on forest trees. Continued assessment of forest inventory plots in the US and other countries will also help document changes in forest productivity and community dynamics under climate change (Jenkins et al., 2003).

3. Research needs

1. Forest productivity continues to increase in the United States (USDA Forest Service, 2001) and Europe (Spiecker et al., 1996; Mäkinen et al., 2003). Whether this is due to rising CO₂ in the atmosphere, enhanced N deposition, or global warming is impossible to say (Aber et al., 2001). Long-term research projects are needed to address this question and to determine if these trends will continue. Little is yet known about whole ecosystem responses to either air pollution or global change (Aber et al., 2001; Karnosky et al., 2003). The current global networks of FACE (Hendrey et al., 1999; Karnosky et al., 2001) and Fluxnet (Buchmann and Schulze, 1999; Baldocchi et al., 2001; Baldocchi, 2003) offer opportunities to sort out trends in ecosystem productivity. Learning more about interactive effects of multiple stresses on realistic ecosystems will require experimental manipulations of ecosystems on a larger scale than yet

conducted (Parson et al., 2003). For example, FACE experiments with multiple, interacting stresses are needed to determine how forests will respond to combinations of air pollution and climate change (Karnosky et al., 2002; Karnosky, 2003). New, less costly and innovative designs are needed for exposing forest ecosystems simultaneously to elevated CO₂, warming environments and air pollutants. Effects of climate change and atmospheric pollution on forest soils and soil microorganisms remain largely uncertain (Zak et al., 2000), although impacts of these changes have been shown to affect soil biodiversity and are in need of additional research (Larson et al., 2002), given their crucial role in nutrient cycling and forest productivity.

2. To begin to understand forest responses to global change, greater effort needs to be directed to the multi-factor (e.g., moisture, nutrient availability) experimental approach and not just to CO₂ and/or O₃ (Shaw et al., 2002). Increasing basic understanding of forest tree responses to air pollution and climate change will help guide process-based modellers to more accurately project forest ecosystem responses to global change (Chappelka and Samuelson, 1998; Pitelka et al., 2001). Research on air pollutant and climate change effects should be done under realistic field conditions using FACE or other appropriate techniques (McLeod and Long, 1999), spatially differing pollutant exposures (Karnosky et al., 2003), and dendro-ecological techniques (McLaughlin et al., 2002). In addition, an increased understanding of stress physiology is important. Large-scale gene expression studies using microarrays laced with thousands of expressed sequence tags (ESTs) offer unprecedented opportunities to study complicated responses to stress and to determine functional patterns of gene expression. Thus, functional genomics will likely play an ever-increasing role in the future and will give physiologists increased understanding of forest responses to interacting stresses. Furthermore, this genomics research can facilitate additional studies on biodiversity. Little is known, for example, about the effects of air pollution and/or climate change on fitness and on genetic diversity.

3. Understanding feedbacks and interactions between forest ecosystems and the atmosphere is critical to understanding and mitigating various aspects of air pollution and climate change. For example, increasing atmospheric CO₂ is closely linked to carbon (C) sequestration in global forests and forest soils, and enhanced reforestation, afforestation and agroforestry have been proposed as methods to mitigate rising atmospheric CO₂. Impacts of such mitigation activities on global forest carbon budgets (Körner, 2003) and biodiversity (Schulze et al., 2002) remain uncertain. Furthermore, little is known about C sequestration under changing climate conditions (particularly changes in temperature and changes in organic matter decomposition), under elevated CO₂, or under interacting elevated CO₂ and elevated air pollutants. Improved forest management and silvicultural practices, advanced genetic selection and improvement,

and biotechnological approaches to improve C sequestration should be coupled with other approaches to mitigate the effects of global change.

4. Another example of a closely linked climate change/air pollution/forest canopy interaction is that of volatile organic compounds emitted by forest trees and involved as precursors in O₃ formation. Under warming conditions, VOC emissions are expected to rise as they have been shown by Sharkey and Singaas (1995) to have a role in protecting leaves from short, high temperature events. Increased VOC emissions and warmer temperatures could contribute to higher O₃ production in the troposphere. How VOCs will respond to rising CO₂ and increasing air pollutants, such as O₃, has been listed as a critical research need both in the US (Fuentes et al., 2001) and Europe (Kellomäki et al., 2001).

4. Conclusions

Approximately 49% of forests of the world will be exposed to damaging concentrations of O₃ by 2100 and area at risk from S may reach 5.9 M km² by 2050, despite large reductions in SO₂ emissions in the developed countries. However, emissions of NO_x have changed little, or have increased. Coincidentally, shifts in precipitation and temperature patterns are occurring. Despite the fact that a number of reports suggest forests are being affected by air pollution, the extent remains uncertain. Routine monitoring systems provide many data, yet often they do not fit statistical requirements for detecting status and trends of forest health. There is a clear need for a new examination of monitoring concepts, designs and choice of ecological indicators especially as much of this information is often considered by decision makers.

Air pollution, climate change and increasing demands upon the forest resources are key factors comprising the global change threat to forest health and sustainability. Considerable scientific effort has been devoted to the enhancement of our understanding of forest responses to global change at the process, organ, system, stand and ecosystem levels. Much work, however, remains to be done, especially in the area of scaling up to landscape in the context of multiple stressors. Integrated approaches are required linking long-term process-oriented empirical studies with pattern-oriented monitoring along defined spatially differing pollutant exposures using ecosystem-based research. New approaches to monitoring will be required if the interactive effects global change on forest health and ecosystem function are to be understood in the 21st century. **Of paramount importance, air quality and climatology measurements must be coupled in time and space to effects analyses. Lack of such coordinated studies has been one of the single most important shortcomings to date.**

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