AIR POLLUTION DAMAGE TO VEGETATION

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Summary

The impacts of air pollutants on vegetation have been studied since the early part of the 20^{th} century, with effort being focused on sulfur dioxide, oxidized and reduced nitrogen, and ozone. Before a pollutant can cause damage, it must first come into contact with the plant. Pollutant uptake depends on climatic conditions and the nature and extent of damage to plants depends on the chemistry and physical characteristics of the pollutant, and on the plant's ability to detoxify it. Typical visible injury symptoms include yellow or reddish spots on the leaf surface, and physiological damage includes reduction in photosynthesis and reproductive potential.

The impacts of ozone on agricultural crops have been quantified by exposing them to the

pollutant in open-top chambers for the growing season. Wheat and soybean are particularly sensitive: injury symptoms have been detected on the leaves in ambient air in parts of Europe and significant yield reductions have been predicted. Atmospheric deposition of reduced nitrogen onto nutrient-limited semi-natural vegetation (unimproved grasslands, heathlands, blanket bog) can cause a shift in the balance of species in these sensitive systems because the nitrogen has a nutrient effect on plant growth. Climatic factors can influence the magnitude of effect of a pollutant. Sulfur dioxide effects on monocotyledonous species (e.g. barley and Timothy grass) are enhanced after exposure to cold temperatures. In some industrializing countries, several pollutants co-exist at potentially damaging concentrations. Fifty percent growth reductions have been reported for crop species in these conditions.

The United Nations Economic Commission for Europe has included the impacts of pollutants on vegetation within international negotiations on the pollutants emission control. Impacts are quantified in terms of exceedance of critical levels or loads of pollutants. In the future, more information will be needed on the influence of pollutants mixtures and on impacts of global climate change.

1. Introduction

In recent decades, the impacts of air pollutants on vegetation have become of political interest. For example, in the 1980s, large parts of the forests of West Germany were found to be suffering from die back of the crowns. Since the forests were of national importance to Germany, the search was on to find the cause of the damage. Air pollutants such as sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and ozone (O_3) were considered to be contributory factors. National and international pollution control initiatives ensued. Today, efforts to reduce the impacts of air pollutants on vegetation are an integral component of pollution control policy, with vegetation-based standards being included in, for example, the World Heath Organization Guidelines, European Commission Air Quality Framework Directive and the Clean Air Act of the USA. This contribution considers the historical development of our knowledge of air pollution impacts on vegetation, how the main gaseous pollutants (sulfur dioxide, oxides of nitrogen, ammonia and ozone) damage vegetation, examples of the main vegetation problems and provides information on an international initiative to reduce pollutant damage to vegetation. However, it should be noted that there are other air pollutants that are potentially damaging to plants growing close to emission sources such as particulates, hydrogen fluoride (HF) and hydrogen chloride (HCl). The impact of these pollutants is not considered here. Further details on the sources, concentrations and pathways of the atmospheric pollutants described here can be found in *Tropospheric Ozone Pollution*, *Sulfur Dioxide and Sulfur Cycles*, *Reduced and Oxidized Nitrogen*, *Suspended Particulate Material (SPM)*, *Gas-Phase (Photo-)Chemical Processes in the Troposphere* and *Pathways of Organic Chemical Contamination in Ecosystems*.

2. Historical Development of Interest

In the early part of the 20th century, scientists began to study the possibility that the components of air in urban areas might reduce the growth of some plant species. The historical development of knowledge in the UK was typical for industrialized countries. In

1925, Cohen and Ruston, reported on the growth of several species at sites in and around Leeds, a city in the industrial north of the UK. They found, for example, that lettuce plants grown at a “clean” site, Garforth, weighed 175 g whereas those grown at a "dirty" site, Hunslet, weighed only 44 g. A loose correlation was found between plant biomass and particulate deposition of sulfur and chlorine, thus suggesting that air pollutants were reducing plant growth in the most industrialized and populated parts of Leeds. However, the effects of air pollution on vegetation below concentrations thought to cause visible damage were dismissed in the 1950s when Katz stated that sulfur dioxide had no effect on plants unless concentrations were above 300 pbb, the concentration he considered to be a threshold for visible injury. Katz stated that "it is hoped that the invisible injury theory has been disposed of, and will not be resurrected...". Some scientists such as Bleasdale, disagreed, but didn't publish results showing that growth reductions could be detected without visible injury being present until the 1970s. Crittenden and Read provided the first conclusive evidence in 1978. They showed that ambient air with sulfur dioxide concentrations below 40 ppb reduced the growth of *Lolium perenne* relative to plants growing in clean air in a filtered air greenhouse. Many sulfur dioxide and oxides of nitrogen exposure experiments were conducted in the UK in the 1980s, and grass species were shown to be particularly sensitive especially during the winter months when the concentrations of these pollutants were highest in the UK.

Ozone pollution, as a causal agent of plant damage was first identified in the USA. A new type of injury was detected on plants in the Los Angeles basin in the 1940s. It was initially described as "weather fleck", and led to premature senescence in tobacco. In 1958, ozone was shown to be the causal agent of "weather fleck" in tobacco. Since then, numerous exposure experiments have been conducted in the USA in the 1970s and 1980s as part of the National Crops Loss Assessment Network (NCLAN) and in Europe in the late 1980s and early 1990s as part of a European initiative to explain crop losses caused by ozone (see Section 5.1). Ozone is now considered to be the most important phytotoxic air pollutant in the USA and Europe.

In the rapidly industrializing countries of Asia, Africa and Latin America, equally rapidly rising emissions of gaseous and particulate pollutants have become a cause of concern in the last two decades. Although impacts on human health are of highest priority, recent surveys and studies have indicated that effects on vegetation are widespread with sulfur dioxide and ozone being identified as the gaseous pollutants causing the most damage.

3. The Mechanisms of Pollutant Damage to Vegetation

Before a pollutant can cause damage, it must first come into contact with the plant. Pollutant uptake (or flux) is dependant on climatic conditions since these influence both the atmospheric conductivity of the pollutant and the receptivity of the plant by an affect on stomatal aperture (i.e. on how wide open the stomatal pores are on the leaf surface). The nature and extent of damage to plants then depends on the chemistry and physical characteristics of the pollutant being considered, and on the plant's ability to detoxify the pollutant.

3.1. Factors Influencing the Uptake of Gaseous Pollutants

The uptake of gaseous pollutants by plants is commonly considered to be analogous to the flow of electrical current through resistors placed in parallel or series. The resistance to transfer from the atmosphere to the sub-stomatal canopy is considered to be the sum of the atmospheric resistance, the boundary layer resistance and the stomatal resistance (see Figure 1).

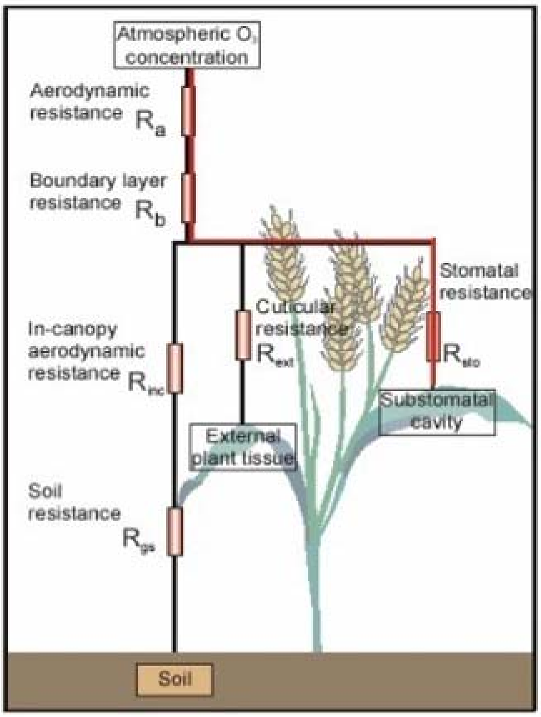

Figure 1: A resistance analogue of ozone transfer between the atmosphere and plant (L.D. Emberson, Stockholm Environmental Institute at York (UK), personal communication)

First, the pollutant must be transported through the turbulent atmospheric surface layer towards the vegetation. It's path is influenced by the aerodynamic resistance for momentum transfer (R_a) and the boundary layer resistance for mass transport (R_b). Conductance through the atmospheric surface layer is driven by both mechanical and thermal forces whilst conductance through the boundary layer is influenced by climatic conditions as well as leaf surface roughness. Boundary layer resistance is low for smooth hairless leaf surfaces during windy conditions when the boundary layer (a motionless band of air around the leaf surface) is thinnest. Stomatal resistance is influenced by the processes controlling stomatal aperture in plants such as temperature, humidity, wind speed, soil moisture content and growth stage. Total gas conductance is the inverse of the resistance to gaseous transfer from the atmosphere to the sub-stomatal canopy.

A simplified model of ozone uptake by the canopy can be used as an illustration. The model uses meteorological and ozone data from the EMEP Lagrangian photoxidant model to calculate canopy stomatal conductance of ozone for a range of crop and tree species. It can be simplified as:

$$G_{O_3spp} = 1/(R_{aspp} + r_{bspp} + r_{sspp}) \quad (1)$$

where G_{O_3spp} is the species-specific stomatal conductance to ozone, R_{aspp} is the bulk atmospheric resistance to the canopy as a whole, r_{bspp} is the species-specific boundary layer resistance and r_{sspp} is the species-specific stomatal resistance. R_{aspp} represents the resistance to mass transfer exerted by turbulence between the top of the surface layer (50 m in the EMEP model) and the surface of the vegetation while r_{bspp} represents the limitation to ozone transfer, predominantly by molecular transfer, across the quasi-laminar boundary layer found adjacent to leaf surfaces. The later is calculated from a function of wind speed and surface properties for a single leaf in the upper canopy. The species-specific stomatal resistance (r_{sspp}) is influenced by the effects of climatic conditions on the aperture of the stomatal pores. Ozone flux (nmol m^{-2} s^{-1}) is then calculated from the product of GO_3 (mol m^{-2} s^{-1}) and the ozone concentration at 50 m height (nmol mol^{-1}).

Stomatal conductance was modelled from experimental data in which this parameter was measured for leaves in the upper canopy over a wide range of environmental conditions (see Figure 2). For example, for Norway Spruce, conductance photosaturated at about 300 μmol m^{-2} s^{-1}, increased to a maximum at about 20 °C and declined at higher tempertures, was at a maximum at vapor pressure deficits (VPDs) below 1 kPa (high humidity) with a linear decline to very low values at VPDs above 3 kPa (dry conditions). Figure 3 illustrates how well the modelled flux compares with the measured flux of ozone, i.e. the explained variance is about 72 percent.

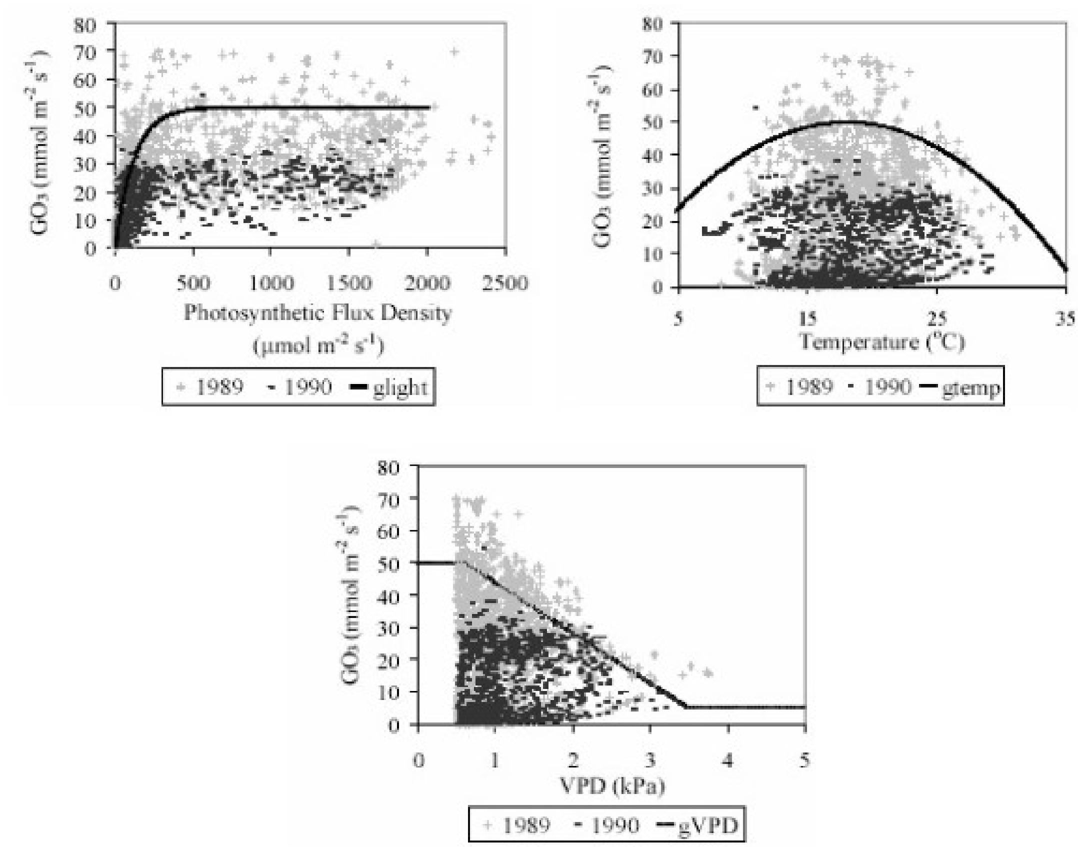

Figure 2: Comparison of the measured data with the g_{light}, g_{temp} and g_{VPD} relationships of the stomatal conductance model. Adapted from Emberson L.D., Wieser G., Ashmore M.R. (2000). Modelling of stomatal conductance and ozone flux of Norway Spruce: Comparison with field data. *Environmental Pollution* 109, 393-402.

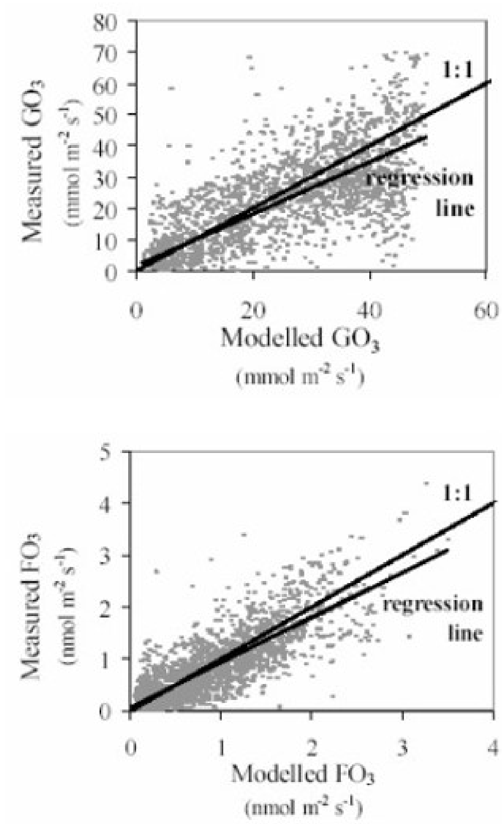

Figure 3: Comparison between measured and modeled stomatal conductance to ozone (G_{O_3}, mmol O_3 m^{-2} s^{-1}) and ozone flux (FO_3, nmol m^{-2} s^{-1}) to Norway Spruce. Adapted from Emberson L.D., Wieser G., Ashmore M.R. (2000). Modelling of stomatal conductance and ozone flux of Norway Spruce: Comparison with field data. *Environmental Pollution* 109, 393-402.

Although the deposition of gaseous pollutants is largely regulated by stomatal resistance, the cuticular surface of the leaf, especially if wetted by rain or dew, also represents a significant sink. For example, Fowler and colleagues showed that 44 percent of annual deposition of ozone to a UK moorland dominated by upland grasses was due to stomatal uptake whereas 56 percent was deposited on the cuticular surfaces. For other pollutants e.g. sulfur dioxide and nitrogen dioxide, deposition to wetted leaf surfaces represents an even larger sink for pollutants. The biological significance of such deposition is unclear, but damage to the cuticle can lead to increased activity of the phylloplane micro-organisms.

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www.icpvegetation.ceh.ac.uk [The web-page for the UNECE ICP Vegetation, an international program that quantifies the impacts of air pollutants on vegetation in Europe and North America. Provides an overview of current knowledge and links to other sites of relevance.].

Biographical Sketch

Gina Elizabeth Mills (formerly Sanders) was born in Nottingham in the United Kingdom in 1959. She studied Biology at the University of Nottingham and studied for a Ph.D. in plant biochemistry at Nottingham Trent University, awarded in 1984. After a further two years of research at Nottingham Trent University into the effects of herbicides on plants, Gina Mills began to study the effects of air pollutants on agricultural crops in the Environmental Physics Department of Nottingham University. Working as a Post-Doctoral Research Fellow she led a small team of researchers studying the impacts of ozone on leguminous crops using field-based open top chambers. In 1991, Dr Mills was appointed as a Lecturer at Nottingham Trent University, specializing in the impacts of environmental stresses on plants. During the following seven years, Dr Mills established the Air Pollution Research Group at Nottingham Trent University. Researchers studied the effect of environmental factors on the responses of plants to ozone and developed modeling methods using Artificial Neural Networks. In 1993, Dr Mills was appointed the Chairperson of the United Nations Economic Commission for Europe International Cooperative Programme on the impacts of air pollutants on natural vegetation and agricultural crops (ICP Vegetation). Five years later, Dr Mills joined the Centre for Ecology and Hydrology at Bangor, UK where she has concentrated on expanding the work program of the ICP Vegetation (involving 150 scientists from 30 countries) and developing a solardome-based ozone exposure system. The latter is currently being used to study the impacts of ozone on upland vegetation. The research work of Dr Mills has been published in over 150 scientific papers, conference papers, book chapters, and state of knowledge reports for the UK government and the United Nations.