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Effects of Acidic Aerosol, Fog, Mist and Rain on Crops and Trees [and Discussion]

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Effects of acidic aerosol, fog, mist and rain on crops and trees

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The most important factors to consider for a complete determination of the toxicity to vegetation of acidic precipitation are: settling velocity, mass transfer rates, capacity to wet surfaces; number, frequency, and duration of events; and chemical composition and concentration. Meteorological factors, such as wind velocity and humidity, also must be considered because they affect the physical, temporal, and chemical properties of precipitation. Climate is important because it influences the capacity of plants to adjust, recover, or compensate for exposure to acidic precipitation. Genotype affects the efficiency of capture and capacity to tolerate acidic conditions.

Aerosol and fog droplets generally are more acidic than mist and rain but they may be less phytotoxic because smaller droplets are deposited and captured less readily by leaf surfaces except when wind velocity is high. Concentrations of acids, mainly sulphuric and nitric acids, in aerosols, fog, mist, and rain in polluted regions, appear to be insufficient to produce acute injury on vegetation except perhaps in the immediate vicinity of intense sources of emissions. Chronic effects of repeated exposure to acidic precipitation, such as the impact on plant nutrition or on processes occurring at the leaf surface–atmosphere interface, and interactions with gaseous pollutants such as ozone, cannot be evaluated at present owing to the lack of information.

Physical properties of atmospheric precipitation

The most important physical properties of atmospheric precipitation are the number concentration, mass concentration, and size distribution of droplets. These properties determine settling velocity, mass transfer, efficiency of capture by surfaces, and capacity to wet surfaces.

Aerosols, fog, and cloud droplets are less than about 10 μm (aerosol) and 60 μm (fog and cloud) in diameter and they are characterized by large number and low mass concentrations (Willeke & Whitby 1975). Mist and rain droplets may be as large as several hundred or several thousand micrometres in diameter, respectively, and they are characterized by small number and large mass concentrations (Pruppacher & Klett 1978). Accordingly, aerosol, fog, and cloud droplets have low settling velocities and remain suspended in the atmosphere. They are not efficiently captured by surfaces nor do they wet surfaces as readily as the larger mist and rain droplets. Velocities of deposition of substances in aerosol and fog droplets are approximately ten-fold less than for the gas, sulphur dioxide, and approximately 100-fold less than for components of mist and rain (table 1).

The physical properties of precipitation fluctuate with time, and changes in droplet diameter have important implications for vegetation. Increase in droplet size leads to increases in deposition velocities and capture by surfaces and the action of gravity on larger droplets compresses droplets and increases the area of contact between droplets and the leaf surface.

Influence of temporal factors

There are three temporal factors that determine the likelihood of effects on vegetation by acidic precipitation: number, frequency, and duration of precipitation events. Increased numbers of exposures (Evans *et al.* 1977), increased durations and decreased time between exposures (Jacobson & van Leuken 1977) increase the likelihood of foliar injury. Frequency

Table 1. Some physical and chemical properties of components of acidic deposition

physical form	common chemical components[1]	particle diameter μm	concentration[1,2] $\mu g\ m^{-3}$	deposition process	deposition velocity[3] $cm\ s^{-1}$	citations
gas	SO_2	—	1300	diffusion, chemisorption	0.2–0.6	Taylor *et al.* 1983; Hosker & Lindberg 1982
aerosol	H_2SO_4 $(NH_4)HSO_4$	0.01–10	40	diffusion, impaction	less than 0.2[4]	Tanner *et al.* 1981; Thomas 1962; Waller 1963
fog, clouds	H_2SO_4 $(NH_4)HSO_4$	1–3		impaction	1–3[4]	Deal 1983; Charlson *et al.* 1978; Pruppacher & Klett 1978
mist	H_2SO_4, HNO_3, $(NH_4)HSO_4$	30–300		impaction, sedimentation	3–50	Dollard & Unsworth 1983
rain	H_2SO_4, HNO_3	300–3000		sedimentation	50–800	Pruppacher & Klett 1978; Shriner *et al.* 1977

[1] In polluted atmospheres not proximal to individual emission sources.
[2] 1300 $\mu g\ m^{-3}$ of SO_2 for 3 h is the U.S. Ambient Air Quality Standard; 40 $\mu g\ m^{-3}$ of sulphate in ambient aerosols occasionally is reached or exceeded in polluted air in the eastern U.S.A.
[3] To dry, inert surfaces.
[4] Dependent on wind velocity.

of precipitation determines the time for recovery, repair, and compensation by the plant for any effects that may have occurred. Duration of precipitation and drying time specify the time during which materials in solution can exchange with materials in or on leaf surfaces. There are wide variations in these temporal factors within and between precipitation events and among seasons.

Intensity of precipitation and total amount of water deposited also can affect plant response to precipitation. Contact angles of droplets and amount of water retained on leaves will be very different for a gentle mist compared with an intense rain-shower. The former may solubilize and make available to the leaf components of particulate matter residing on the leaf surface, while the latter may move such substances from leaf surfaces to the soil. These factors also may influence the spread of diseases because rain aids the dissemination of spores, and water on leaf surfaces fosters the infection process for some pathogenic organisms (Shriner 1980). The influence of acidic precipitation on processes occurring at the leaf surface is an important subject about which little is known at present.

Influence of meteorological factors

Meteorological conditions affect the physical and chemical properties of precipitation and meteorological factors integrated over time (climate) affect plant response to components of precipitation. The most important factors in this category are wind, humidity, temperature, and solar radiation.

Wind velocity determines the rates of impaction of suspended aerosol and fog droplets on to vegetative surfaces (Clough 1975; Little 1977). At higher elevations where plants are exposed either to high winds or are enveloped in fog and passing clouds for many hours, boundary-layer resistance is diminished and interception of substances in precipitation is greatly enhanced (Hosker & Lindberg 1982; Lovett *et al.* 1982; Dollard & Unsworth 1983). Greater quantities of components of precipitation are deposited on vegetation growing in mountainous areas downwind of urban and industrial regions because of the combination of higher concentrations in fog and cloudwater, longer durations of exposure to precipitation, and greater rates of deposition (Waldman *et al.* 1983). Wind also increases exposure of undersides of leaves to precipitation but it reduces the amount of water retained on leaf surfaces.

Temperature, humidity, and wind velocity determine evaporative potential of the atmosphere and evaporation rates affect droplet size and chemical concentrations as droplets are transported and deposited. The residence time of liquid on leaf surfaces also is affected by evaporation rates. Conditions that lead to the formation of dew or fog in a polluted atmosphere can produce highly concentrated solutions on leaf surfaces because the volume of water is low, and water-soluble pollutants readily dissolve in the liquid (Wisniewski 1982).

Meteorological conditions may be as important for plant response to pollutants as they are for accumulation of pollutants in the atmosphere. Pollution episodes occur when changes in meteorological factors limit atmospheric dispersal and produce ground-level exposures (Scorer 1968). Similarly, effects on vegetation occur when meteorological conditions favour rapid deposition of pollutants and the development of plants in a susceptible physiological condition (Mukammal *et al.* 1968). Furthermore, damage to vegetation, defined as loss in aesthetic, economic, or ecological value, occurs when either time or conditions do not allow adjustment, recovery, or compensation for the initial injury that may be detected by both physiological changes or foliar lesions.

Chemical properties of precipitation

There are two chemical characteristics of precipitation that determine the likelihood of effects on vegetation: composition and concentration. The three ions hydrogen, sulphate, and nitrate, appear to be the main chemical constituents that affect vegetation in ambient precipitation not associated with individual emission sources. There are associations among chemical properties, physical properties, and temporal characteristics of precipitation that are important for correct estimation of dose (Jacobson & Troiano 1983). Excessive concentrations of free hydrogen ions produce symptoms of acute toxicity in vegetative and reproductive tissues of plants that may lead to altered growth and development. Sulphate (Thomas *et al.* 1943) and nitrate are essential nutrients utilized in plant metabolism and, even in excessive quantities, they may not be phytotoxic. In fact, chloride salts are considerably more toxic to plant tissues than sulphate (Eaton *et al.* 1971). Both sulphate and nitrate may be absorbed directly from precipitation by leaves and indirectly by roots from the soil medium. Foliar absorption provides nutrients from precipitation in higher concentrations but for relatively short and intermittent periods. Root absorption of ions from precipitation provides lower concentrations because ions are diluted and retained in the soil. However, root uptake may proceed continuously and roots are structured for effective absorption of ions.

The occurrence of acidic droplets in the atmosphere was reported in London as early as the 1920s (Waller 1963), in Los Angeles in the 1940s (Middleton *et al.* 1950), and in Ottawa in the 1960s (Dubois *et al.* 1969). Recently, more intensive determinations have been made of the chemical composition of acidic fog in California (Waldman *et al.* 1982) where, under some conditions, day-time aerosol is converted into night-time fog (Jacob *et al.* 1983). The most commonly found strong acids in aerosol and fog droplets are sulphuric and nitric, with lesser amounts of hydrochloric and organic acids (Tanner *et al.* 1981). Ammonium ions often are present in large quantities and ammonium sulphate and other sulphate and organic compounds have been identified in polluted aerosols (Charlson *et al.* 1978; Ferek *et al.* 1983). Sulphate concentrations in aerosols peak in summer and winter, and nitrate in winter in the United States (Mueller *et al.* 1980). The concentration of sulphate in aerosols of the eastern U.S. is ten to one hundred times greater than nitrate, and sulphate generally is 20–33% of the mass of aerosols. Aerosol acidity tends to follow the same diurnal pattern as photochemical oxidants with higher concentrations occurring during the afternoon (Tanner *et al.* 1981). In the eastern U.S., concentrations of sulphuric acid may be higher in rural aerosols than in urban aerosols because there are more neutralizing cations emitted in urban areas. Furthermore, sulphate has a longer lifetime in the atmosphere than nitrate and, therefore, sulphate is transported over larger distances (Harrison & Pio 1983).

The chemical composition of rain has been well documented in industrial countries in recent years and in the U.S. a large variation in composition exists between different regions. Greatest concentrations of acids and total deposition occurs in the eastern U.S. (Altshuller & Linthurst 1983). Relatively few rain events, that usually occur in the summer, account for a major share of the annual deposition of hydrogen, sulphate, and nitrate. Rainfall also contains lesser quantities of metals, organic compounds, and highly reactive transient compounds that have been less well characterized (Altshuller & Linthurst 1983). pH values obtained from precipitation monitoring networks with rigorous quality control procedures in the eastern U.S. give ranges of pH 3–3.5 up to greater than 6. Most rain events are in the range of pH 3.5–5 and growing season volume-weighted mean pH values may be as low as 3.9 in certain portions of the eastern U.S.

Effects of acidic mist and rain on vegetation

Foliar response

Exposure of vegetation to acidic fog produces lesions and abscission of leaves (Metcalfe 1941), symptoms that usually can be distinguished from injury caused by gaseous pollutants (Middleton *et al.* 1950). Pure sulphuric acid aerosol is not effective in causing foliar lesions unless additional water is deposited on leaves (Thomas 1951). Surface characteristics of the leaf, such as roughness, pubescence, morphology, and orientation of the leaf, control the rate of aerosol deposition and retention of aerosol droplets (Chamberlain 1967; Wedding *et al.* 1975; Little 1977). Rain falling after deposition of aerosols can remove most of the deposited material depending on the type of substances deposited (Wedding *et al.* 1977), the intensity of rain, and the duration of time between aerosol deposition and rainfall.

High humidity may increase the capture of aerosols by leaves and the severity of injury to vegetative tissues (Lang *et al.* 1980; Gmur *et al.* 1983). In sufficient concentrations, sub-micron aerosols have produced marginal and tip necrosis, whereas larger droplets have produced localized necrosis distributed over the leaf surface (Lang 1978). Sub-micron aerosols also have caused chlorosis, wilting of leaf tips, and accelerated senescence and abscission of leaves (Gmur *et al.* 1983). The concentrations of acidic aerosol required to produce noticeable injury and measureable reductions in growth of plants in experiments are in the range of 10–100 mg m^{-3} (Lang 1978; Gmur *et al.* 1983). Reported measurements of acids in ambient aerosol and fog droplets may be as high as 25–50 μg m^{-3} in polluted urban air in the U.S. (Thomas 1962; Scaringelli & Rehme 1969; Atkins *et al.* 1972; Tanner *et al.* 1981; Ferek *et al.* 1983). There also are reports of 157 and 678 μg m^{-3} for acidity of fog in Los Angeles (Mader *et al.* 1950) and London fogs (Commins 1963), respectively. Concentrations of acidity in ambient aerosols usually are at least 100 times less than concentrations that are required to injure experimental plants.

Susceptibility of species and cultivars

Several generalizations can be derived from investigations in which the responses of two or more species or cultivars have been compared in a single series of experiments under similar conditions of treatment.

Dicotyledonous plants generally are more susceptible than monocots, and root and leafy vegetables are more susceptible than forage, grain, or fruit crops (Lee *et al.* 1981; Cohen *et al.* 1982). Needles of coniferous trees are less likely to develop lesions from exposure to acidic mist or rain than foliage of hardwood trees and herbaceous plants (Jacobson & van Leuken 1977; Wood & Bormann 1974, 1977; Evans & Curry 1979; Haines *et al.* 1980; Scherbatskoy & Klein 1983). Radish leaves are more susceptible than barley (Harcourt & Farrar 1980) and more susceptible than lettuce, wheat, and alfalfa (Evans *et al.* 1982). Golden Delicious apple trees are more susceptible than McIntosh or Delicious (Proctor 1983), but, in other tests, McIntosh was more susceptible than Golden Delicious (Forsline *et al.* 1983). The basis of differences in susceptibility between species and cultivars has not been discovered as yet.

Some species have been tested for both injury and effects on growth and yield by two or more investigators, and there are similarities and conflicts in results. *Phaseolus vulgaris* has been used in several investigations and the highest pH values at which foliar symptoms were reported are: pH 3.2 (Johnston *et al.* 1982), 3.1 (Evans & Lewin 1981), 2.5 (Hindawi *et al.* 1980), and 2.0 (Ferenbaugh 1976). With *Raphanus sativus*, Evans *et al.* (1982) found reductions in hypocotyl growth at all pH values beginning with 5.6 (compared with untreated control plants). Lee *et al.* (1981) and Cohen *et al.* (1982) found decreases in growth at pH 3.5 and 3.0 but increases at pH 4.0. With *Glycine max*, Evans & Curry (1979) and Keever & Jacobson (1983) found foliar lesions at pH 3.4, while Irving & Miller (1981) found lesions at pH 3.0.

There are many possible reasons why conflicting results have been found when the same species have been exposed to acidic precipitation in different studies. Different cultivars within a species may respond differently to acidic precipitation, or dissimilar environmental conditions may alter plant response. Conflicting results may come from the use of different techniques and procedures for exposure to acidic precipitation. Even when pH values are the same, differences in rain intensity, duration, and frequency can produce widely divergent rates of acidic deposition (Jacobson 1983). Other explanations are given in a later section.

Relations between foliar lesions and growth reductions

Foliar injury is directly related to fresh market value for leafy vegetables because marketability is determined by appearance. But, for growth and yield (biomass) of crops, foliar injury and yield may not be closely related (Lee *et al.* 1981; Cohen *et al.* 1982). There are several possible explanations for this poor correlation: (i) timing of exposures in relation to stage of plant development; (ii) effects on partitioning of photosynthate; and (iii) adjustment, recovery, or compensation.

Young seedlings and plants, at the stage of rapid development of the harvested product, generally are most susceptible to yield reductions. Exposure to acidic precipitation at other stages may lead to foliar injury but not necessarily to a detectable effect on growth or yield measured weeks or months later. Injury may be trivial, in relation to effects produced by other constraints on growth and yield, particularly if the injury occurs late in the growing season.

Based on genotype and environmental conditions, plants allocate dry matter to different organs. This allocation process may be altered by exposure to acidic precipitation (Troiano *et al.* 1983). With plants that flower and set fruit, developing fruit and seed may continue to compete successfully for photosynthate to the detriment of root or foliage development.

Plants adjust to environmental conditions and, given sufficient time, they may recover and compensate for foliar injury. Little information is available on the capacity of plants to overcome initial injury by acidic precipitation. The presence of solutes of nutritional value, such as sulphate and nitrate in precipitation, may contribute to recovery. Some indications of increased growth after exposure to acidic precipitation have been obtained (Wood & Bormann 1977; Lee *et al.* 1981; Evans *et al.* 1982; Cohen *et al.* 1982; Troiano *et al.* 1982).

Comparative responses of field and greenhouse-grown plants to acidic precipitation

There seems to be a consistent relation between the relative susceptibility of plants grown under controlled conditions (glasshouses and chambers) and susceptibility of plants grown in the field. Where these comparisons have been made, acidic precipitation generally has elicited foliar lesions and growth reductions at lower conentrations of acids in plants grown in pots in the glasshouse or chambers than with the same species grown in the field and exposed to similar treatments. This relation has been found for *Phaseolus vulgaris* (Evans & Lewin 1981), *Glycine max* (Irving & Miller 1981; Keever & Jacobson 1983), *Raphanus sativus* (Evans *et al.* 1982; Troiano *et al.* 1982), and other crop species (Cohen *et al.* 1982). Glasshouse-grown plants also are more susceptible to effects of gaseous air pollutants such as ozone (Jacobson 1982). Therefore, information from glasshouse and chamber studies provide conservative estimates of plant response to acidic precipitation.

Comparison of phytotoxic concentrations of acidity in simulated and ambient precipitation

One approach to synthesizing the large amount of information available from glasshouse and chamber studies is to compare the levels of acidity that cause injury to experimental plants with the levels of acidity reported for ambient rainfall. Accordingly, the number of published reports of the highest acidity (pH) at which injury was found on foliage of individual species of crops and trees was plotted against pH on the same graph as the frequency distribution for pH of rain events at two sites in the U.S. Department of Energy MAP3S monitoring network that display the most consistently acidic rainfall (figure 1). The results show that most reports of foliar injury are for pH values of 3.5 or less, acidities generally greater than those occurring in ambient rain. Taking into account the greater susceptibility of experimental plants grown under controlled conditions and the high acidity of these two sites, one can conlude that there is a low risk of foliar injury to field-grown vegetation from exposure to current levels of acidity

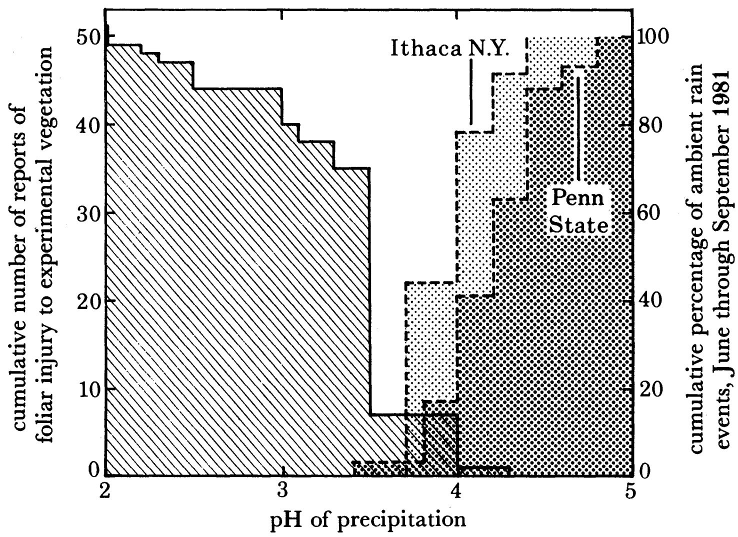

FIGURE 1. Comparison of acidity of ambient rain at two sites in the northeastern U.S. with acidity causing foliar injury to experimental vegetation grown in greenhouses or chambers.

in precipitation in the eastern U.S. Verification of this conclusion must come from tests of effects on yield foliar injury and yield are not always correlated. Unfortunately, conflicting results have been obtained from initial experiments designed to test effects of acidic precipitation on yield of field-grown crops (Altshuller & Linthurst 1983; Jacobson & Troiano 1983).

Some explanations for contradictory results of experiments on effects of acidic precipitation on vegetation

Problems associated with experimental approaches to the study of effects of acidic precipitation on vegetation have been described previously (Jacobson 1980) and continued research has uncovered some additional difficulties. Conflicting results may result from the use of different measurement procedures, experimental designs, or techniques of statistical analysis.

The sensitivity of observations of foliar symptoms is dependent on whether they are made visually with no magnification, with a hand lens, or with a microscope. Slight symptoms of injury may be masked by or indistinguishable from injury by insects, pathogens, nutritional disorders, climatic extremes, or gaseous air pollutants.

The detection of significant effects of treatments is affected by the variability of response of the plant material. Detection is enhanced, but the relevance of results to actual conditions is diminished when plants of a narrowly defined genotype are used such as vegetatively propagated material or seeds from a single tree. Use of commercial seed sources or seeds selected to be

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

representative of populations of natural vegetation makes detection of effects more difficult but the relevance of results to actual conditions is greatly increased.

Detection of effects can be enhanced by use of a large number of replications at the expense of the ability to extrapolate from experimental conditions to ambient field conditions. When relevance to widely varying concentrations of components of precipitation that occur within and between events is emphasized, the number and range of treatments may be increased at the expense of replication.

Interpretation of results also is dependent on the selection of the error term in statistical analyses. The capacity to detect effects is increased when the error term includes only plant-to-plant error but interpretation of results applies only to the specific conditions of the individual experiment. Use of a treatment interaction term obtained from experiments replicated in time provides interpretations that are more useful because they apply to a range of conditions.

Interpretation of results also is dependent on the nature of treatments that are performed and contrasted. Comparisons between plants treated with simulated acidic rain and those exposed only to ambient acidic rain or to ambient acidic rain and simulated acidic rain do not provide a satisfactory basis for evaluating the impact of ambient acidic rain. In addition to differences in deposition of acids, there are differences among treatments in amounts of water and other ions deposited, and in the frequency, duration, and intensity of rainfall. Until the significance of these factors for plant growth and yield is determined, such comparisons must be treated with great caution.

Another factor that produces differences in interpretation is the nature of the control treatment. Plants treated with simulated rain at pH 5.6 have been widely used as controls even though it is unlikely that the pH of rain was close to 5.6 before the use of fossil fuels (Segueira 1982). Nor is it likely that the pH of rain in the northeastern U.S. will be near 5.6 if anthropogenic emissions of pollutants were drastically reduced. Comparisons between plants treated at low pH and at pH 5.6 may exaggerate the effects of reducing the acidity of precipitation.

When contradictory results have been reported, it has not been possible to make rigorous comparisons because of inadequate descriptions of experimental procedures, conditions, and methods of statistical analysis. The following information should be provided in all publications in addition to other items that may be appropriate for the particular experiment: (i) treatments: droplet size distribution, droplet number distribution (for aerosol and fog), rain intensity, duration, and frequency of occurrence, components of precipitation and their concentrations, total deposition of water (for fog, mist, and rain) and individual ions; and (ii) environmental conditions before, during, and after treatment: temperature, humidity, wind speed, solar radiation, and daylength.

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Discussion

S. G. Garsed (*Imperial College, Silwood Park, Ascot, Berks.*). We need to be careful in our use of the term 'injury'. Recent demonstrations of a lack of absolute relation between acute injury to plants and their growth responses imply that there must be more than one mechanism by which plants are damaged, and consequently more than one mechanism of plant resistance. The classic symptoms of visible injury reflect damage to one particular part of the plant, namely the plasmalemma. It does not automatically follow that other physiological processes in the same plant are equally sensitive. Therefore the methods we choose to measure the effects of pollutants, and indeed our interpretation of what the sensitive processes are, need to be examined with great care.

K. Mellanby (*Watt Committee on Energy. Monks Wood Experimental Station, Abbots Ripton, Huntingdon PE*17 2*LS, U.K.*). The previous three speakers have discussed the effects of acids on grass, crops and trees. I consider that we should also consider the effects on lichens. It is well known that lichens are very susceptible to damage from gaseous SO_2. Thus where we find a luxuriant growth of shrubby lichens, we can be sure that SO_2 levels are low – generally below 20 μg m^{-3}. We find many shrubby lichens in areas such as Scandinavia and the Black Forest, where damage from 'acid rain' is reported. Thus lichens may serve to distinguish between where dry deposition of gases occurs, and where acid rain operates.

The distribution of lichens suggests that acid emissions may affect the environment in three different ways. First we have the direct dry deposition of toxic substances near their source of emission. Until recently this caused widespread damage to plants and buildings in cities and industrial areas in Britain. This has been largely controlled. Smoke is much reduced and SO_2 concentrations at ground level have been lowered by discharging flue gases from tall chimneys. Acute phytotoxicity is now rare, damage as reported by the previous speakers may extend for some distance, but further off levels are so low that damage is avoided.

However, this may not entirely solve the problem. Rain hundreds of miles from the source of pollution is contaminated and may damage freshwater organisms, and possibly crops, trees and the soil. This damage is generally attributed to 'acid rain' and I suggest that this itself has two forms. Confusion may be avoided by distinguishing between primary acid rain and secondary acid rain.

Primary acid rain is caused by the washout from the atmosphere by rain of substances emitted in urban and industrial areas and has been known in Britain for more than 100 years. It may be very acid – levels of pH 3 have been reported. It is accompanied by gaseous pollutants, which may often do more damage than the rain. It, like the dry deposition, is primarily a local problem. As we move away from the source of the emissions the rain becomes less and less acid.

But the problems in Scandinavia are attributable to secondary acid rain which is quite different. It is produced when the oxides of sulphur and nitrogen are transformed to sulphuric and nitric acid, something that goes on slowly (especially for sulphur) and may have its effect hundreds of miles from the source of pollution.

As long as it does not rain, the low concentrations of acid in the air do little damage, for small amounts are deposited. However, heavy rain washes the acid from a huge volume of air onto a limited area of ground. It may then be channelled into a small lake, or stored in snow to be concentrated and liberated in the first melt in spring.

A report of the American National Academy of Sciences suggests the deposition of acid may be linearly related to the amount of emissions. European workers find no such direct correlation. The explanation is that the Americans are considering mainly primary acid rain, the Europeans secondary acid rain and its effects after chemical transformation much further from source.

I realize that I have over-simplified the matter. Where there are many sources of pollution, the same site may receive a mixture of primary and secondary acid rain. Nevertheless I believe that this recognition that acids act in three forms, not just two (dry and wet deposition) ways may help to remove some of the present confusion.

M. H. Unsworth (*Institute of Terrestrial Ecology, Bush Estate, Penicuik, Midlothian, U.K.*). The first two papers at this meeting discussed mainly the average acidic deposition received in various regions or areas. The next three papers showed the large variation in responses between and within plant species. If we want to evaluate the ecological effects of deposition, I believe that we must try to identify the elements of the ecosystem that are at risk by virtue of either their physical exposure or their biological sensitivity. Could any of the previous speakers be persuaded to speculate on which sites and species they feel have high risk potential? For example, are there reasons why upland conifers might be particularly at risk? Would isolated plants receive more deposition by various pathways than plants growing in canopies? Within a mixed plant community does deposition on individual plants differ much from the mean?

R. Lines (*Forestry Commission, Research Division, Northern Research Station, Roslin, Midlothian, U.K.*). Forestry Commission Trial Plantations in the industrial Pennines include 26 species in over 20 experiments planted between 1951 and 1977. Because early growth was poor, sulphur dioxide pollution was suspected. Volumetric recorders could not be used because of the absence of electricity supply, so a network of 24 lead dioxide gauges was established in 1956. Results over three years showed sulphation rates for these remote upland sites which were sometimes as high as those in urban areas. The reason appears to be the higher wind flow through the gauges. Which is the better analogue for tree response, a volumetric instrument recording only concentration of sulphur dioxide or the gauge that integrates concentration and wind flow? Tree growth and survival were shown to relate broadly to the sulphation rates of the lead dioxide gauges after allowing for other obvious site factors (Lines 1983).

Sitka spruce (*Picea sitchensis* (Bong) Carr.), which is recognized as a species that grows well on very exposed (unpolluted) sites, performed poorly in the Pennines in the 1950s and has been shown by Rutter and Garsed to be sensitive to sulphur dioxide. Marked growth improvement of this species was noted in these plots in the late 1960s coinciding with lower sulphur dioxide levels in surrounding towns. This was checked in 1978–82 by a second series of lead dioxide gauges, six of which were located on the same sites as those in 1956; the latter showed a mean reduction in sulphation rate of 50%. This improvement in growth in the Pennines contrasts with the reduction in diameter increment of Norway spruce (*Picea abies* Karst.) in northern Federal Germany noted by Hütterman earlier in this symposium.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES