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PROCEEDINGS OF THE INTERNATIONAL WORKSHOP ON THE EFFECTS OF ACID PRECIPITATION ON VEGETATION, SOILS, AND TERRESTRIAL ECOSYSTEMS

Held at Brookhaven National Laboratory
June 12-14, 1979

LANCE S. EVANS AND GEORGE R. HENDREY, Editors

COSPONSORED BY
THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
AND THE UNITED STATES DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
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Cosponsored by the United States Environmental Protection Agency,
under the Interagency Agreement EPA-79-070681,
and the United States Department of Energy.

Organized by: Lance S. Evans,¹ T.C. Hutchinson,² and G. Abrahamsen.³

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International Workshop on the Effects of Acid Precipitation
On Vegetation, Soils, and Terrestrial Ecosystems

Executive Summary

The extent to which plants and terrestrial ecosystems are impacted by acid precipitation is a topic of intense interest to scientists and regulatory agencies of governments. Investigations into the nature of such impacts have been conducted for over a decade. To assist the United States Environmental Protection Agency in evaluating the current state of knowledge concerning the effects of acid precipitation on vegetation, soils, and terrestrial ecosystems, an International Workshop was organized at Brookhaven National Laboratory in June 1979. The workshop brought together leading scientists in these fields of research from Europe, Canada, and the United States.

The objectives of the workshop were to determine the (1) levels of current knowledge of the effects of acid precipitation on vegetation, soils, and terrestrial ecosystems; (2) research needed in these areas to understand the environmental impacts of acid rain; and (3) to help coordinate research groups to avoid excessive duplication of research. The workshop was designed so that researchers in the areas of effects of acid precipitation on vegetation, soils, and whole ecosystems approaches could communicate effectively. The diversity in research backgrounds of the participants is shown in the diversity of research priorities and the types of anticipated research needs. In order to assess the degree of consensus in setting priorities for research, each participant was asked to reply to specific questions. A poll was taken on a number of questions and responses of YES, NO, or INSUFFICIENT KNOWLEDGE were used. Each participant also ranked the relative importance of various research objectives. The results of the priority rankings are shown in Tables i, ii, and iii.

Vegetation Effects

There was a general consensus that acid rain at extreme ambient levels, or in artificial systems that simulate extreme ambient levels, causes injury to plant tissues. One major area of concern was thought to be plant reproductive systems, but the overall significance of plant injury is unknown. Although a few participants thought that acid rain caused injury in terms of plant metabolism almost everyone agreed that research was necessary in this area. The most important priorities in the area of effects of acid rain on crops were: (1) an evaluation of effects on crop sensitivities as reflected in yields; (2) interaction of acid rain with other pollutants including particulates on plants; (3) dose-rate effects studies; and (4) identification of crucially sensitive life cycle stages. Table i gives a complete list of research priorities for crops.

Soil Effects

Few participants thought that ambient acid rain loadings have altered soils to such a degree that plants are affected at present but many thought

that acid rain could cause some alterations in soil. A large percentage of participants thought that acid rain has significantly altered soil pH in some areas. The most important research priorities were in the areas of the effects of acid rain on (1) increased leaching of exchangeable plant nutrients such as Ca, Mg, K, Fe, and Mn from soils; (2) reduced availability of phosphorus; and (3) increased soil acidification. Table ii gives a complete list of research priorities for soils.

Terrestrial Ecosystem Effects

All participants agreed that there are alterations in terrestrial ecosystems from acid precipitation. However, no demonstrated harmful effects were presented from natural ecosystems. Although the group thought there were demonstrated harmful effects on vegetation, a large percentage also thought there were demonstrated positive effects as well. All agreed that long-term research programs should be established in natural and artificial ecosystems to evaluate the effects of acid rain. With regard to research priorities, studies should be directed toward (1) the interaction of acid rain with toxic elements such as Al, Fe, and Mn; (2) the effects on nutrient cycling, and (3) effects on the nitrogen cycle. Table iii gives a complete list of the research priorities for terrestrial ecosystems.

Table i

List of Research Priorities Concerning Effects of Acid Precipitation on Crops

Rank	Research Area	Number of ^{a/} Responses-
1.	Crop sensitivity (yields)	7
2.	Interactions with other pollutants including particulates	5
3.	Dose-effects studies	4
3.	Identification of crucial sensitive life cycle stages	4
3.	Effects of pollination/pollen viability	4
4.	Physiological responses/stomatal function	3
4.	Effects of plant pathogens	3
4.	Direct and indirect effects	3
5.	pH effects within cells	2
5.	Metabolic effects	2
6.	Sulfate concentrations and effects within cells	1
6.	Lime compensation experiments	1
6.	Trace element deficiency development	1
6.	Effects on storage problems	1
6.	Identification of special regional problems	1
6.	Effects on N-fixation	1
6.	Economic impacts	1
6.	Hidden injury, i.e., chronic effects	1
6.	Rhizosphere effects	1
6.	Nutrient budget impacts	1
6.	Seed germination	1
6.	Standardized methods/microcosms, etc.	1

a/

The participants listed three major priorities of research on the effects of acid rain on crops. The cumulative number of responses in each category is given.

Table ii

List of Priorities on Effects of Acid Precipitation on Soils

Rank	Research Area <u>1/</u>	Average Score <u>2/</u>
1.	Effects of soil acidification on leaching of exchangeable plant nutrients, such as Ca, Mg, K, Fe, and Mn. Effects of acidification on the rate of weathering of soil minerals.	7.3
2.	Effects of simulated acid rain on leaching losses of Al from soils.	6.5
3.	Effects of acidification on the availability of P to plants and the availability of phytotoxic elements such as Al.	6.1
4.	Natural soil formation processes in humid regions tend toward acidification. How does acid precipitation effect this process?	6.0
5.	Effects of acidification on soil microbiological processes such as N fixation and breakdown of residues. The following processes may be influenced by soil acidification: a) Nitrogen fixation by <u>Rhizobium</u> bacteria on legumes and by <u>Azotobacter</u> b) Mineralization of N from forest floors c) Nitrification of ammonium compounds d) Overall decay rates of forest floor material and, therefore, the rate of availability of stored nutrients.	5.6
6.	Determine the factors that establish susceptibility of soils to acidification.	

Table ii cont.

7. Determine the effects of acid precipitation on largely uncultivated areas that have soils that are poorly buffered and may be most susceptible, i.e., forest and wilderness areas of the United States and Canada.
8. Determine the effects of heavy metal deposition associated with acid precipitation.
9. Determine the significance of quantities of plant nutrients such as N and S that are being added to soil by dry deposition and precipitation. In some ecosystems these inputs may be important in the maintenance of the nutrient budget.

1/

The statements taken from "A National Program for assessing the Problem of Atmospheric Deposition (Acid Rain), a report to the Council on Environmental Quality by NADP (NC-141)" were rephrased in the form of research priorities.

2/

Participants were asked to rank the statements from 10 (highest rank) to 1 (lowest rank). Average scores represent the mean value obtained when the total values from all ballots were divided by the total number of ballots.

Table iii

List of Research Priorities Concerning Effects of Acid Precipitation
on Terrestrial Ecosystems

Rank	Research Area	Number of _a Responses-
1.	Interaction with toxic elements (Al, Fe, Mn)	9
1.	Effects on nutrient cycling	9
2.	Effects on nitrogen cycle	8
3.	Long-term studies on forest plots (with other interactive factors applied)	7
3.	Studies on species and regional sensitivities	7
3.	Litter decomposition	7
4.	Identification of sensitive soils	6
5.	Studies of forest productivity (growth analysis)	5
6.	Studies of sulfur compounds in soils	4
7.	Pollination of plants	3
7.	Refinement of methods for measuring forest production- sensitive to a 5% change in productivity	3
7.	Soil microorganisms	3
8.	Identification of indicator species	2
8.	Reproduction of forest species	2
8.	Leaf surface processes	2
8.	Ecosystem model development and refinement	2
8.	Use of microcosm and greenhouse studies	2
8.	Effect of foliar leaching on nutrient status of an ecosystem	2
8.	Interaction with biota agents	2
9.	Effects on soil organic matter	1

Table iii cont.

9. Development of measurable dose parameters to determine effects	1
9. Effects on cation exchange capacity	1
9. Effects on plant pathogens	1
9. Effects on soils	1
9. Studies on dry deposition effects	1
9. Controlled field exposures - measurement and evaluation of experimental results	1
9. Effects on mycorrhizae	1
9. Interactions with other pollutants	1
9. Interaction effects with sulfurous SO ₂ on leaves	1
9. Gradient deposition studies	1
9. Tree physiology	1
9. Effects on tundra vegetation	1

a/

The participants listed five major priorities of research on the effects of acid rain on terrestrial ecosystems. The number of responses in each category is given.

ABSTRACT

The objectives of the International Workshop on the Effects of Acid Precipitation on Vegetation, Soils, and Terrestrial Ecosystems at Brookhaven National Laboratory in June 1979 were to determine the (1) levels of current knowledge of the effects of acid precipitation on vegetation, soils, and terrestrial ecosystems; (2) research needed in these areas to understand the environmental impacts of acid rain; and (3) to help coordinate research groups to avoid excessive duplication of research. The Workshop was designed so that researchers in the areas of effects of acid precipitation on vegetation, soils, and whole ecosystem approaches could communicate effectively.

There was a general consensus that acid rain at extreme ambient levels, or in artificial systems that simulate extreme ambient levels, causes injury to plant tissues. A major area of concern of acid rain injury was thought to be plant reproduction. The overall levels of significance of plant injury among various plant species remain unknown. The most important priorities in the area of effects of acid rain on crops were (a) an evaluation of effects on crop yields and (b) interaction of acid rain in combination with pollutants on various plants. Few participants thought that ambient acid rain loadings have altered soils to such a degree that plants are affected at present, but many thought that acid rain could cause some alterations in soils. The most important research priorities were in the areas of the effects of acid rain on (a) increased leaching of exchangeable plant nutrients and (b) alterations in phosphorous availability. All participants agreed that there are alterations in terrestrial ecosystems from acid precipitation. However, no demonstrated harmful effects were presented from natural ecosystems. Further research on the effects of acid rain on terrestrial ecosystems should be directed mostly toward (a) the interaction of acid rain with toxic elements such as Al, Fe, and Mn and (b) on the effects on nutrient cycling, especially that of nitrogen.

WORKSHOP ORGANIZATION

The Workshop was held June 11-14, 1979 at Brookhaven National Laboratory, with the objectives of determining the (1) current knowledge in specific research areas, (2) research needs in light of energy and environmental considerations, and (3) levels of research coordination necessary to avoid excessive duplication of research efforts. In addition, the workshop was designed so that researchers working on effects of acid precipitation on (1) vegetation, (2) soils, and (3) whole ecosystem approaches could communicate effectively. It was hoped that communication among these three groups might lead to research collaboration that could bring a more holistic view to the research approaches. The following persons participated:

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INTERNATIONAL WORKSHOP ON THE EFFECTS OF ACID PRECIPITATION
ON VEGETATION AND TERRESTRIAL ECOSYSTEMS

Opening Remarks
Dr. George Hendrey

This is the second workshop dealing with the environmental effects of acid precipitation organized by Brookhaven National Laboratory and sponsored by the Environmental Protection Agency. The first one, the International Workshop on Limnological Aspects of Acid Precipitation was held in September 1978.

The informal gathering of a limited number of experts in this area was proposed as a means of obtaining frank and open discussions. I hope that you will be most candid in your comments and discussion on the topics to be addressed.

This workshop was organized to determine:

1. Current knowledge in specific areas.
2. New or expanded research needs.
3. Means of coordination to avoid duplication.

After nearly a decade of research, we should try to achieve consensus among leading researchers concerning the known effects of acid precipitation on plants. Can we answer these questions?

1. Does acid rain in nature cause injury to plant tissue and is such injury significant to
 - a. reproduction of the plant?
 - b. the metabolism of the plant?
 - c. the production of food or fibre?
2. Does acid rain alter soils to such a degree that plants are significantly affected?
 - a. Are nutrients depleted to a degree which would reduce soil fertility?
 - b. Is pH depressed to a degree which would interfere with plant or microbial processes or nutrient cycles?
3. Are forest ecosystems altered? (Is productivity reduced?)

These questions are of great interest to regulatory agencies and legislative committees of our respective governments. The charge to you at this workshop is to do your best to answer these questions and to summarize current knowledge in these topic areas.

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OVERVIEW OF THE ACID PRECIPITATION PROBLEM

European Situation

Dr. Gunnar Abrahamsen

Discussion Leader

Precipitation in rural areas of Norway has low concentrations of SO_2 , less than $20 \mu\text{g}/\text{m}^3$ which is equivalent to 7 ppb (parts per billion). Elevated levels of hydrogen, sulfate, ammonium, and nitrate in rainwater decrease the pH from around 6 to 4 or 5 and the amount of hydrogen ion deposition is 50-100 micro equivalents hectare⁻¹ annually. This condition results from the fact that over 10% of all rain events have a mean pH of less than 4.0. Excess sulfate deposition from rain and snow is 5-25 kg S/hectare/yr. Deposition of the various oxides of nitrogen have not been studied in much detail in part because the techniques for detection of NO_x have not been refined to the same degree as for SO_2 . Today, the best estimates of NO_x deposition rates in Norway are between 2 and 20 kg N/hectare/year and the nitrogen deposited is composed of equal amounts of nitrate and ammonium.

Effects on terrestrial biota may be divided into (a) above- and (b) below-ground level effects. The above-ground effects can be subdivided into (i) effects on physical injury to vegetation, (ii) nutrient leaching from vegetation, and (iii) chemical injury to vegetation. The below-ground effects may be subdivided into (i) soil acidification, (ii) nutrient leaching processes, and (iii) alterations in plant growth.

In field studies, spruce needles exposed to the least acidified water had the largest wax accumulations. Wood and Bormann (1974) have shown an increase in K^+ , Ca^{2+} , and Mg^{2+} leaching from foliage exposed to simulated rain of low pH. Current year needles of spruce had the highest K^+ concentration in plots exposed to simulated rain of the lowest pH. The various acid rain treatments did not affect the K^+ concentration in older needles, but the concentration of K^+ was lower in older than in first year needles. The magnesium content of needles was highest in specimens treated with simulated rain of low pH.

At present, there is a need for studies of the effects of leaching on field and laboratory grown plants in which the soil is not covered. Long-term studies are needed with perennial plant species.

Studies with soils should be performed in a similar manner. How does acid precipitation change soils with respect to plant growth and plant productivity? Does a change in nutrient level induced by simulated acid rain change the chemical and biological processes of plants or soils? We should look for mechanisms of change since these mechanisms may be used to predict long-term changes in other areas. Some important soil mechanisms to study are (a) bicarbonate and aluminum systems, (b) efficiency of exchange of cations by H^+ , and (c) input and output of anions in soils (compare input from rain and long-term leaching rates). For example, if we compare levels of nitrates and sulfates, 12% of all nitrates added by rainfall will be leached from the watershed while 8% will be retained by the watershed. These percentages can be compared with the percentage of sulfates. About 19% of all sulfates that enter a watershed will be leached while only 7% will be retained. These rates will, of course, differ among various soil types.

A large input of sulfate usually involves considerable leaching of hydrogen ions in the A horizon. No chemical alterations have been found in the B horizon. One would expect higher leaching rates in loams than in podzols. Soils of low base saturation should have low leaching rates while soils of high base saturation should have high leaching rates.

Rates of weathering differ among various soil types. Weathering rates of podzols is in the range of 80-140 meq/m²/yr. The input of nutrients in rainwater in Norway is about 50-100 meq/m²/yr. Most weathering occurs in the B horizon. This horizon is probably not affected by acid rain. We need better estimates of soil weathering for various soil types under a variety of environmental conditions.

Under irrigation conditions the base saturation diminishes with a decrease in rain pH in a podzol soil. The concentration of soil magnesium decreased concomitantly with a decrease in applied rain pH for each year.

How does acid rain affect soil fertility? On a short-term basis the loss of nutrients from foliage by accelerated leaching may be compensated for by a short-term increase in nutrient uptake by roots. However, over a long-term basis plant growth may be limited if significant amounts of nutrients are leached from the soil. The levels of Mg may become limiting on a long-term basis.

In some field tests an increase in growth rate of Scotch pine with acidified irrigation water was observed during 1977. There was an increase in the concentration of nitrogen and sulfur in needles. No significant differences in growth rate were shown with either Norway spruce or loblolly pine grown under similar conditions. The difference in growth of scotch pine in 1977 was not evident in 1978. The increased growth rate of scotch pine in 1977 may have been due to an increase in ammonium content of the acidified irrigation water. It is possible that Mg could become limiting on a long-term basis under these circumstances. More work is necessary to assess how this input of sulfur compounds in rainwater would affect soil microbiological processes.

Base saturation was changed by acidified water applications. The Ah horizon (0-3 cm), which has a significant concentration of organic matter, showed no alterations during the first year (1974) of application. A slight alteration occurred during the second year and some substantial changes occurred during the fifth year (1978). Only a slight change in the cation exchange capacity occurred in the Bh (3-5 cm) or Bs (8-13 cm) horizons during the tests.

United States Situation

Dr. Lance Evans
Discussion Leader

The United States has an energy problem. The high price of imported petroleum and the risks associated with nuclear power make coal a more attractive source of energy. Can we use this coal for energy production without a significant degradation of the environment?

Sulfur is a by-product of energy utilization when either coal or oil is used as a fuel source. It has been determined that the per capita daily emission of SO_2 in the United States is about one-half kilogram. About 60% of all atmospheric sulfur worldwide, is derived from anthropogenic sources. In such areas as eastern North America, anthropogenic emissions of sulfur are so great that natural sources are insignificant in the total sulfur budget. About 20-50% of this atmospheric sulfur is incorporated into aerosol particles that may be incorporated into rainwater.

North America has about 35% of the earth's economically recoverable coal reserves, about 255 billion metric tons. Moreover, North America has about 31% of the earth's known coal reserves, 410 billion metric tons. In 1977, the United States produced about 0.6 billion metric tons of hard coal, an increase of 150% above the output in 1960. If this rate of coal utilization increases 2.3% annually, coal production will be 1.0 billion metric tons for the year 1995. However, if the rate increases to 4% annually we should use 1.0 billion metric tons by 1987 (Griffith and Clarke, 1979).

About 77% of all coal in the United States is used for electrical generation. Most of the remainder is used for industrial purposes (Griffith and Clarke, 1979). Moreover, most fossil fuel utilization in power plants occurs east of the Mississippi River (Shriner, McLaughlin, and Baes 1977).

A portion of the sulfur dioxide emitted into the atmosphere is deposited onto the earth's surface. However, some is converted to more oxidized and hydrated forms. The chemical reactions involved have been reviewed (Whitby, 1978). Under most circumstances, sulfates are formed. These components usually assume an acidic nature (e.g., $(\text{NH}_4)_2\text{SO}_4$, NH_4HSO_4 , and H_2SO_4). Much of this sulfate is associated with aerosol or with particles in the atmosphere that may travel for thousands of miles. Most of this particulate sulfate is associated with accumulation mode aerosol sizes between 0.15 and 0.50 μm in diameter with a geometric mean of 0.48 μm (Whitby 1978 Tanner et al., 1979) so that very little sulfur is found in the sedimentation size range (above 2 μm in diameter, Whitby, 1978).

Air samples taken within the United States show a high concentration of sulfates in the Northeastern United States (EPA). Moreover, the concentration of sulfate in the atmosphere has increased during the period from 1961 through 1972 (USEPA, 1975). One must anticipate that the concentration of sulfate will increase as the concentration of SO_2 increases. A plot of the concentration of non-urban SO_2 with sulfate concentration shows that the sulfate concentration increases as the concentration of SO_2 increases (Figure 1; data taken from USEPA 1975).

The chemistry of precipitation has been determined with precision in recent years. Modern analytical techniques have enabled investigators to make correlations among the concentrations of various constituents. The pH of

rainfall in the Northeastern United States has decreased from the period between 1965-1966 and 1972-1973 (Likens, Bormann, and Johnson, 1972). More recent analyses indicate a correlation coefficient of 0.97 between H^+ concentration and the sum of $SO_4^{=}$ and NO_3^- in rainwater samples (Tanner et al., 1979). These data indicate that the increased acidity in rainwater is associated with inputs of nitrate and sulfate from anthropogenic sources. The contribution of acidity in rain given by sulfate and by nitrate must be evaluated by additional research.

The isopleth data show annual average pH values. These averages do not show that some rain events have a much higher pH level than the annual average (Raynor and Hayes, 1978). Moreover, if subsamples of entire rainfalls are taken, rain collected during the first portion of the rainfall is usually more acidic than rain collected later (Raynor and Hayes, 1978). Terrestrial ecosystems are not subjected to annual averages but are subjected to rainfall moment by moment. Thus the pH of water within a given rainfall may be more important than the pH of the rainfall averaged over the time period.

The duration of the rainfall event is important since rainfall of longer duration tends to produce more phytotoxic effects than a fall of shorter duration (Jacobson and Van Leuken, 1977), and we know there is much variation in the duration and pH of various rainfalls. Experiments must be performed in order to detect correlations between the duration and pH of rainfalls and the phytotoxic effects observable. Moreover, since the dry deposition of acidic components of particulates occurs in the absence of rain the time period between rainfalls may be important because a longer time between rainfalls may allow for greater aerosol deposition.

Figure 1. Relationship between the average concentrations of sulfur dioxide and sulfate in the atmosphere at 18 locations in the United States for the years 1970 through 1973. Data computed from United States Environmental Protection Agency (1975).

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Canadian Situation

Dr. T. Hutchinson
Discussion Leader

What is the distribution of sulfur in the air environment of North America? How much sulfur is transported from the United States to Canada and vice versa, annually? The province of Ontario produces about 2.1 million tons of sulfur per year, compared with 14 million tons annually produced in the United States. On an annual basis about 2.0 million tons is transported from the United States to Canada. At the same time about 0.6 to 0.4 million tons of S are transported from Canada to the United States and to the surrounding oceans, respectively. The precipitation of Canada is quite acidic.

In James Bay for example, rain has fallen with pH in the range 5 to 4.5. A good example of a point source of sulfur air pollution is the nickel and copper smelters of Sudbury, Ontario. Although 69% and 42% of the Ni and Cu are deposited within a 60 km radius of the smelters about 98% of the sulfur is carried 50-60 km from the sources. At the same time about 40% of the nitrogen and 50% of the fly ash are deposited within 50-60 km of the smelters.

The pH of rainfall is influenced by the presence of the smelters. Rainfall within 10 km of smelters is usually alkaline due to the presence of fly ash while the rainfall at distances greater than 10 km is acidic due to inputs of sulfur and nitrogen power plants and smelters usually produce concentrations of SO₂ that affect plant metabolism. However, on a long-term basis, these point sources produce particles that are deposited on soils. In general, constituents of the particulates are more readily taken up by vegetation than are constituents of natural soils. In this way, the products of anthropogenic activity are preferentially accumulated by vegetation.

Within the Sudbury area, SO₂ causes severe effects on vegetation but the devastation in this area cannot be attributed to SO₂ injury alone. In more remote areas with no visible vegetation injury, there is a 60-70 % reduction in photosynthesis due to elevated SO₂ and O₃ concentrations. The effect of this loss in photosynthesis on plant productivity or survival is unknown. In this regard elevated levels of copper in soils usually decrease the effects of high SO₂ levels. The decreased sensitivity to SO₂ by copper is usually attributed to altered stomatal function.

In Canada, most of the prairie soils of the central provinces are deficient in sulfur while most of the eastern soils have sufficient or excess. In soils that have inputs of sulfur and acidity there is an increased mobilization of Fe, Al, and Zn. These metals can be toxic at high concentrations. Increased uptake of these three elements due to increases in soil acidity has not been fully documented, however. On the other hand, the deposition of Cu and Ni in soils around Sudbury has been so heavy that many seedlings did not become established seven years after the implementation of the "super stack."

The Smoking Hills section of Canada is another example of excess SO₂ fumigation. In this area natural burning of bituminous shale, with large amounts of sulfur, causes high concentrations of SO₂. This ground level release of SO₂ has produced soil acidity readings at about pH 3.0 with some natural pools with a pH below 2.0. Soils of Smoking Hills also have high concentrations of Se, As, Sn, and Va. When soil concentrations at various depths Ca, Va, and As are plotted at various distances from Smoking Hills, Ca levels are low near the site and increase at more remote locations. In an opposite fashion both Va and As are high near Smoking Hills and are much lower at more removed locations.

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MECHANISMS OF FOLIAR INJURY

Dr. Lance S. Evans
Discussion Leader

When precipitation comes into contact with foliage the extent of injury may be a function of the degree of leaf wetting. The degree of leaf wetting seems to be a function of the physical forces between water molecules for (1) other water molecules and (2) the foliage surface. The most convenient way to visualize the degree of foliar wetting is via the contact angle. The advancing contact angle of a water droplet on a surface is the angle between the surface and the tangent plane of the droplet (Figure 2). A zero angle would indicate complete wettability while an angle of 180° demonstrates almost no wetting. Contact angles of pure water drops may be as small as 31° on Phragmites communis to greater than 150° on Triticum aestivum and Lupinus albus (Linskens, 1950; Hall et al., 1965).

In general, the contact angle of most leaves is determined by the chemical and physical characteristics of cutin and of the epicuticular waxes, and the surface roughness (Martin and Juniper, 1970). The wettability of foliage is regulated mostly by the chemical characteristics of the epicuticular waxes. If the cuticle is removed the advancing contact angle is reduced markedly (Fogg, 1948).

Solutions must penetrate through cuticle layers or through stomata. It has been postulated that cuticles are perforated with micropores (Crafts, 1961). Cuticular pores are numerous in specialized areas such as at the bases of trichomes, hydathodes, glandular hairs (Schnepf, 1965), the water-absorbing scales of Bromeliaceae (Haberlandt, 1914), and the stigma tips (Konar and Linskens, 1966). However, the postulate that cuticular pores exist in all plant cuticles is not well documented (Martin and Juniper, 1970).

The cuticle itself is composed of layers of hydroxy-fatty acids that are interleaved with waxes. These hydrophobic layers should inhibit penetration of polar substances. When the impregnating waxes are removed by soaking in ethanol or isopropylchloroacetamide, the resultant cuticles are more permeable to polar substances (Darlington and Barry, 1965). It was presumed that the removal of the wax interlayers within the cuticle structure by organic solvents increased the permeability.

Penetration of stomata by rain is thought to be infrequent if it occurs at all (Adam, 1948). Several studies have attempted to determine the rate of entry of leaf surface solutions into leaves via stomata. Apparently, the rate is either very low or no penetration occurs (Gustafson, 1956, 1957; Sargent and Blackman, 1962). Therefore, stomatal penetration of aqueous solutions is relatively unimportant; the main route of entry of both hydrophilic and hydrophobic substances must be through the cuticle.

Non-polar molecules should penetrate the cuticle at a faster rate than polar molecules because of the non-polar nature of both cutin and the waxes of the cuticle (Norman et al., 1950). More polar compounds, such as inorganic ions and water, may preferentially enter the leaf via pectinaceous channels that penetrate through the cuticle (Roberts et al., 1948). It is postulated that the ratio of cutin to wax in the cuticle greatly influences the degree of penetration of polar substances (Martin and Juniper, 1970).

Figure 2. Diagram of large (A) and small (B) contact angles of liquid drops on a solid surface. The advancing contact angle is the angle between the surface and the tangent plane of the droplet. Figure reproduced from Martin and Juniper (1970).

A number of factors influence the rate of sorption of chemicals by leaf cuticles (Orgell, 1957). Ninety percent of all cuticles of apricot plants grown out-of-doors exhibited cuticular cracks caused by insect punctures, wind abrasion, etc. which permitted rapid penetration of all substances (see also Furmidge, 1959). It seems reasonable that growth chamber and/or greenhouse grown plants would have fewer cuticular cracks than plants grown out-of-doors. However, the entire cuticle thickness is usually greater in plants grown out-of-doors (Martin and Juniper, 1970).

Solution pH may also affect cuticular penetration rate. In experiments with isolated apricot leaf cuticles, the rate of penetration of acidic substances increased with a decrease in pH. In contrast, the rate of penetration of basic substances increased with a pH increase. These relationships between pH and sorption rates with apricot cuticles (Orgell, 1957) have been verified with isolated cuticles (McFarlane and Berry, 1974) and intact bean leaves (Evans, unpublished results) exposed to buffered solutions.

Cuticles should not be considered inert, non-differential barriers to ion permeability. The relative permeability coefficients of isolated cuticles to various mono and divalent cations differ by as much as a factor of 6. Moreover, penetration of potassium was much higher at alkaline than at acidic pH levels (McFarlane and Berry, 1974). $^3\text{H}_2\text{O}$ water, $^{35}\text{SO}_4^{2-}$, and $^{86}\text{Rb}^+$ were applied to the adaxial surfaces of leaves at several pH levels. $^{35}\text{SO}_4^{2-}$ penetrated faster at pH 3.9 and 3.3 than pH 6.1 (Table 1). In contrast, $^3\text{H}_2\text{O}$ pervaded faster at the higher pH levels, and $^{86}\text{Rb}^+$ entered foliage at similar rates for all pH levels tested (Table 1). So, although cuticles are only slightly permeable to inorganic ions, there is differential or selective penetration.

This idea of differential or selective uptake of chemical constituents by foliage is reinforced by other experimental data. The penetration of chemicals into foliage is affected by both metabolic and passive processes. Reversible diffusion through the cuticle is followed by metabolically controlled uptake through cellular membranes (Prasad and Blackman, 1962). There are many examples of light enhanced uptake (Bennett and Thomas, 1954; Gustafson, 1956; Sargent and Blackman, 1965) as well as inhibition by protein synthesis inhibitors (Jyung and Wittwer, 1964).

Some regions of the cuticle are more permeable than others. Hull (1964) demonstrated that the basal portions of trichomes are more permeable than adjacent areas. In addition, cuticles of guard cells and subsidiary cells are preferred sites of absorption (Dybing and Currier, 1961; Sargent and Blackman, 1962). Linskens (1950) and Leonard (1958) found that the cuticle near veins offers a preferential site for absorption of water-soluble materials. These studies are germane because about 95% of all lesions on a variety of plant species following exposure to simulated acid rain occurred near the bases of trichomes, at guard and subsidiary cells of stomata, and along veins (Evans, Gmur, and Kelsch, 1977; Evans, Gmur, and Da Costa, 1977, 1978).

Removal of epicuticular waxes by rainwash has been commonly observed (Purnell and Preece, 1971; Mueller et al., 1954; Martin and Juniper, 1970). Evidence from scanning electron microscopy studies suggests that acid rain may increase the rate of the removal of epicuticular waxes (Lang, Krupa, and Shriner, 1978). Further research is needed, however, before this mechanism can be verified as a functionally significant impact of acid rain on vegetation.

Table 1

Incorporation of several isotopes into middle leaflets of first trifoliolate leaves of Phaseolus vulgaris after 1 1/2 hours of exposure to the isotope in buffers.

pH of buffer	Cpm of $^{35}\text{SO}_4^{2-}$	Cpm of $^{86}\text{Rb}^+$	nCi of $^3\text{H}_2\text{O}$
6.1	801 $\pm$ 101	582 $\pm$ 94	45 $\pm$ 4
3.9	2240 $\pm$ 203	671 $\pm$ 292	40 $\pm$ 3
3.7	2328 $\pm$ 185	558 $\pm$ 148	45 $\pm$ 4
3.5	2117 $\pm$ 172	581 $\pm$ 143	-
3.3	2154 $\pm$ 232	471 $\pm$ 96	32 $\pm$ 2

Middle leaflets of first trifoliolate leaves of 17-day-old plants were exposed to isotopes in citrate-phosphate buffer. Leaves were exposed to either 50 $\mu\text{Ci/ml}$ of $^{35}\text{SO}_4^{2-}$ (spec. act. 894 mCi/mg sulfur), 50 $\mu\text{Ci/ml}$ of $^{86}\text{Rb}^+$ (spec. act 0.124 $\mu\text{Ci}/\mu\text{g}$ Rb), or 0.01 mCi of ^3H per ml of tritiated water. Leaf samples consisted of one set of three leaf discs with a total area of 115.5 mm². Means and standard errors of three sets of leaflet discs from four different plants during one representative experiment for each isotope are given.

The cuticle may also act as an ion exchanger, possibly both with cells and with leaf surface moisture. Epstein (1953) demonstrated binding of ions by an ion-binding carrier in the cuticle. This binding involves an expenditure of energy by cells (Reichenburg and Sutcliffe, 1954). Moreover, since carboxylic groups of cutin may not all be esterified, free hydrogen ions may exchange with other cations (Brieshorn and Boss, 1964). Cations are exchanged more readily compared with anions because cations bind to the negatively charged polymeric chains of both hydroxy-carboxylic acids of cutin of the polymers of galacturonic acid residues of pectin. In this way, these substances act as ion-exchangers. pH has an important influence on this ion-exchange system. At low pH, the exchangers are present but can no longer accept cations because they are saturated with protons. If the exchanger is exposed to more neutral pH conditions some of the protons may be released. Acid-rain-induced lesions on vegetation occur mostly on leaves and reproductive structures (Gordon, 1972; Jonsson and Sundberg, 1972; Wood and Bormann, 1974; Ferenbaugh, 1976; Evans, Gmur, and Da Costa, 1977, 1978; Evans and Curry, 1979). Simulated rain at about pH 3.4 is the highest pH at which visible lesions on leaves have been observed. Lesions are located preferentially at bases of trichomes, in guard cells, and in epidermal cells above veins (vascular tissues). A large percentage of the leaf area may exhibit lesions. About 0.5%, 2-3%, 5.10%, and 10-15% of the leaf area of pinto beans is injured after several exposures to simulated acid rain at pH levels of 3.0, 2.7, 2.5, and 2.3, respectively (Evans, Gmur, and DaCosta, 1977; Hindawi et al., 1977).

Densities of both trichomes and stomata of these structures per unit leaf area are highest in young leaves and lowest in fully expanded leaves. The amount of visible leaf injury is most pronounced on pinto bean leaves that have reached full expansion (Evans, Gmur, and DaCosta, 1977, 1978; Evans and Curry, 1979). Since the amount of visible leaf injury does not coincide with the density of either stomata or trichomes at full leaf expansion, other factors must be involved in predisposing leaves to injury. The stage of maximum leaf expansion may be correlated with a temporary decrease in cuticle thickness in some areas, or cell wall components for a short time may synthesize different types of cutin. Most injury to foliage by simulated acid rain occurs on expanding or recently expanded leaves and needles. Young (14-day-old) birch seedlings are much more sensitive than older (six-week-old) seedlings (Wood and Bormann, 1974). Evans et al. (1978) demonstrated that leaves had just reached full expansion were more sensitive to simulated acid rain than unexpanded and fully-expanded leaves. Gordon (1972) demonstrated that needle elongation will be inhibited if simulated acid rain solutions are applied to immature pine fascicles. This result was confirmed by Hindawi and Ratsch (1974).

Acid precipitation may have many effects on vegetation (Tamm and Cowling, 1977). Individual cells of the epidermis may be injured upon initial exposure to acid rain (Evans, Gmur, and Da Costa, 1977, 1978). Moreover, acid rain may cause some alterations in the cuticle and/or functioning of the guard cells. The rate of gas exchange was much greater in foliage exposed to simulated rain of pH 2.7 to 3.4 than in foliage exposed to rain of pH 5.7 (Figure 3). These results suggest that foliage exposed to acid rain may be more subject to wilting or water stress as well as more subject to greater internal exposure of gaseous air pollutants.

Figure 3. Adaxial leaf resistance in middle leaflets of first trifoliolate leaves of *Phaseolus vulgaris*. Measurements were initiated on 14-day-old plants. Resistance measurements were obtained 4 hr after each daily 20-min application of simulated rain when no surface water was present. Values represent mean and standard error of values obtained from four plants per treatment. At day 2 the resistances of plants exposed to pH 2.7 was significantly higher than leaves exposed to pH 5.7. Leaves exposed to pH levels of 3.4 and 3.1 were significantly different from pH levels of 5.7 and 2.7 on day 2. There were no significant statistical differences between resistances of leaves on day 4 and day 7. On day 11 the resistance of leaves exposed to pH 2.7 was significantly lower than all other treatments. Leaves exposed to pH 5.7 had significantly higher resistance levels than all other treatments on day 11. Resistances of leaves at pH 3.4 and 3.1 were never significantly different. A decrease in leaf resistance is associated with a greater rate of gas exchange. The results indicate that gaseous pollutants such as ozone or sulfur dioxide would penetrate foliage more quickly in plants exposed to simulated rain of low pH than in plants exposed to simulated rain of more neutral pH levels.

CHARACTERIZATION OF FOLIAR INJURY

Dr. David Shriner
Discussion Leader

Injury to plant foliage by acid rain takes place mostly where a pooling of water persists for a long time. Generally, injury occurs in areas of natural leaf depression.

The number of lesions is related to the time and frequency of exposures to acid rainfalls. Injury is seen most frequently near the junction of veins and tips of veins. Lesion starts with injury to one or two epidermal cells. This injury usually forms a depression on the leaf surface. Foliage injury has been described in the literature as (1) pitting, (2) necrotic lesions (Wood and Bormann, 1974; Hindawi et al., 1977), (3) erosion of epicuticular waxes (Lang, Krupa, and Shriner, 1978), (4) chlorosis (Shriner, Decot, and Cowling, 1974; Evans, Gmur, and Da Costa, 1977; Jacobson and Van Leuken, 1977), (5) bifacial necrosis (Hindawi et al., 1977), (6) spotting (Shriner, Decot, and Cowling, 1974), (7) premature abscission of needles in conifers (observed only with severe injury after repeated exposure to very low pH levels; Jacobson and Van Leuken, 1977), and (8) galls (hypertrophy and hyperplasia; Evans et al., 1978).

Delayed plant maturation of 1-2 weeks has been measured in pinto beans and soybeans. These results suggest that impaired photosynthesis has occurred. This delay in maturation may be related to premature senescence and abscission of more mature leaves.

Has there been documentation of acid rain injury in nature? It has been suggested that leaf injury on pin cherry may be due to acid rain but no documentation has been forthcoming (Likens, unpublished). Russetting of Golden delicious apples has been attributed to substances in rain (Creasey, unpublished). Acidic components from volcanic fallout have been said to cause injury to tomatoes on Hawaii (Kratky et al., 1974). At present there are no published reports of plant injury in nature due to acid rain in the continental United States.

Environmental conditions may play a large role in determining whether a biological effect will occur. Environmental factors such as temperature, relative humidity, light intensity, duration of rainfall, intensity of rainfall, and duration between rainfalls may influence the degree of injury. The duration of the low pH rainfall during the event versus the average pH of the entire event may be an important consideration. The manner in which these characteristics influence the biological responses of plants to pH are unknown. More quantitative studies must be performed to evaluate these environmental variables.

In one Norwegian forest plot experiment, a spruce-birch forest was exposed to simulated rain of pH 4.0, 3.0, 2.5, and 2.0. Small lesions developed. There was little indication, however, of significant impact on canopy species, of significant changes in cover species, or of species diversity of understory plants unless exposed to rainfalls of pH 2.5 or lower (Abrahamsen, 1980). More detailed studies are needed to view possible acid rain impacts in nature.

Documentation of acid rain injury in nature is different from documentation of injury due to gaseous pollutants. In many cases where gaseous pollutant exposure occurs, there is a gradient of gas concentrations from a single

source. Since acid rain does not result from a single source, and since it does not occur at predicted times (one can have high pH rains and low pH rains very close together), researchers will have a difficult task assessing actual environmental effects. Moreover, since acid precipitation occurs over a widespread area with a wide range of soil types, climatic and other environmental variables may alter the effects in such a manner that no consistent pattern can be established.

Present experimental data from laboratory and field experiments are difficult to compare. The duration of rain events, history of exposure to gaseous pollutants, agronomic or forestry practices, and plant-to-plant, and species-to-species variations may be too great to produce results sufficiently consistent to establish cause and effect relationships. It may be advantageous to convert all units for each treatment to hydrogen ion concentration per unit leaf area per unit time. One attempt at this has been performed by Jacobson and Van Leuken (1977). In these studies, if the duration and rainfall pH are plotted against percent leaf area injured a series of lines are produced.

Contribution of Ian Nicholson

One study close to Edinburgh in central Scotland showed that twice as much sulphur was deposited as dry deposition as with wet deposition. Over a 2-year period about 10% of rain (daily collection) was below pH 4.0. Data from a network of precipitation samplers (collected monthly) dispersed over northern Britain showed that acid precipitation (pH < 4.5) affected a large proportion of the area.

Needles of Scots pine (Pinus sylvestris) of the same provenance were sampled from a site in an area exposed to polluted atmospheres and one in a 'clean air' area. Assessments of epicuticular waxes, using a scanning electron microscope, showed that wax erosion was accelerated in polluted conditions.

METABOLIC EFFECTS OF ACID RAIN ON FOLIAGE

Dr. Irmgard Ziegler
Discussion Leader

On a biochemical basis we must consider the reactions of (1) protons, (2) the anions of sulfite, sulfate, and nitrate, and (3) sulfur dioxide.

Action of Protons

To reach the cells the protons in the water layer must overcome cuticular, stomatal, and/or plasmalemma resistances. Assuredly, protons will have an affect on membrane structure and function. Although the cytoplasm of membrane-bound organelles resists dramatic changes in pH, the membrane itself may be altered significantly. Studies with isolated chloroplasts show that internal pH remained relatively constant over several days if the chloroplasts were exposed to high acidity levels. However, the photosynthetic capacities of these chloroplasts were inhibited. Since amino acids are thought to be significant in buffering the cytoplasm, large changes in metabolism may have to arise before significant changes in pH occur.

In this way, one would expect that acid precipitation would initially affect enzymes. Researchers could probably test this hypothesis most easily with isolated protoplasts from leaves. These changes in enzyme function are probably manifested initially by changes in membrane permeability and/or transport mechanisms, as these seem to be the most important functions of membrane proteins. Such experimental parameters as (1) cation leaching, (2) proton gradients for phosphorylation, (3) ATP turnover rates, and (4) activities of extracellular enzymes may help us understand the molecular basis of injury that results from high proton concentrations. Every plant tissue may have its own pH and buffering capacity. Sensitivity of plants to acid precipitation may be determined by an analysis of their buffering capacities. If differential sensitivity is not due to buffering capacity it is probably due to membrane integrity.

Action of Sulfite Counter Ion

Sulfite is a competitive inhibitor of the photosynthetic enzyme ribulose diphosphate carboxylase, with respect to bicarbonate. Low concentrations of sulfite (below 0.5 mM) produced an increase in CO₂ fixation rates in Chlor-ella. If the concentration of sulfite exceeds this, CO₂ fixation is inhibited. There is also an increase in methionine content. This competitive inhibition of RudP carboxylase activity is thought to occur by the following reaction:

Bisulfite may change the activity of enzymes by changing the protein conformation.

In contrast to ribulose diphosphate carboxylase, PEP carboxylase has a much lower sensitivity to SO_2 or bisulfite concentrations. This difference in sensitivity has produced elevated concentrations of glycolate. These results suggest that plants that have the C-4 photosynthetic pathway may be less sensitive to SO_2 than plants that have only the C-3 pathway. It seems that C_4 plants are relatively insensitive to SO_2 but not all insensitive plants are C_4 plants.

Interaction of pH and HSO_3^-

When sulfite, S_4 is present in a cell it may be present as SO_3^- , HSO_3^- , and $\text{H}_2\text{O}\cdot\text{SO}_2$ depending upon the pH of the solution. At a high pH most of the sulfite is in the form of SO_3^- . As the pH is lowered the predominant sulfur form becomes HSO_3^- . However at pH levels of 3.0 the concentration of $\text{SO}_2\cdot\text{H}_2\text{O}$ increases markedly as the concentration of added Na_2SO_3 increases. A critical level of $0.1 \times 10^{-3} \mu\text{M}$ of $\text{H}_2\text{O}\cdot\text{SO}_2$ seems important.

CHEMICAL EFFECTS ON SOILS

Dr. William McFee
Discussion Leader

Experimental results have demonstrated that simulated acid precipitation can (1) cause leaching of Ca, Mg, K, Fe, and Mn; (2) reduce the level of base saturation; and (3) cause loss of Al in soils. The effects of acid rain applications may be counteracted or masked by applications of lime and nitrogen fertilization.

One hundred cm per year of rain at pH 3.7 would provide 0.2 eq of H^+ $m^{-2}y^{-1}$. In contrast, nitrogen fertilization at the rate of 100 kg N hectare⁻¹ as ammonia provides 1.4 eq of H^+ m^{-2} . To counteract such acid inputs 4 metric tons hectare⁻¹ of lime provides 8.0 eq of base m^{-2} . As a result, we can neglect effects on agricultural soils that are usually limed. The only effect that acid rain might have on limed soils is a requirement for addition of slightly more lime.

Some experimental results suggest that there is an acceleration of mineral weathering in natural soils due to acid rain. X-ray diffraction studies of B horizon layers show no change in the composition after five years of leaching. However, subtle changes in the cation-exchange capacity of soils with respect to the chemical aspects of liquid and solid soil phases are difficult to predict.

Phosphate availability should be reduced as the pH of the soil is reduced (Hewitt, 1975). However, no reports have documented reduced phosphate availability due to inputs of acid rain.

In experiments with lysimeter plots at the EPA Lab in Corvallis, Oregon, thirty-six alder and sugar maple trees were placed in large boxes embedded in the soil. Simulated rains of pH 5.7, 4.0, 3.5, and 3.0 were applied to trees and soil beneath the trees. Plant growth appeared the same at all pH levels. The highest litter-leaching rates of sulfate occurred at the highest pH levels used. The rate of Ca^{++} leaching was greater than that for $SO_4^{=}$. In plots exposed to simulated rain at pH 3.0, the litter leachate pH was 3.5 to 4.0.

At a depth of 20 cm it took 30 weeks to detect excess $SO_4^{=}$ in the soil solution in plots exposed to rain of pH 3.0. At the other pH values used, sulfate levels remained constant at about 1 mg/l over the entire 140 week test period.

Over a 120 week period the amount of Mg leached at 20 cm was greater for plants exposed to rain of pH 3.0 than at pH 3.5, 4.0, and 5.0. The amount of Mg leached from plots exposed to pH 3.5 was almost the same as those from plots exposed to pH 4.0 or 5.0. These results suggest the Mg may be preferentially leached from soils exposed to acid rain. These experimental results obtained with accelerated acid rain applications should be compared with the results obtained from longer-term, lower intensity rain application systems.

These results coupled with other experimental results suggest that natural soils would not be altered rapidly by inputs of rain having a pH greater than 3.0. These results don't take into account microbiological aspects of soils.

The susceptibility of soils to acid rain should be defined, and appropriate criteria for ranking relative susceptibility categorized. Soils that are susceptible to acid rain may be defined as those soils that lose productivity

after exposure to acid rain. In general, soils with free carbonates should be more resistant to pH change than soils with few or no carbonates. Soils of low cation exchange capacities should be more susceptible than soils of high CEC. Soils with high clay and/or organic matter contents should have more exchange sites for protons. It seems self-evident that soils that can be altered chemically by acid rain should be those that have a low resistance to pH change or those that would exchange nutrients easily. Soils sensitive to acidification should be soils that have a pH between 5.0 and 9.0 and a low cation exchange capacity. Soils already below pH 5.0 are probably not sensitive in the sense that they would be further acidified, however, if they have a low cation exchange capacity they may be damaged by increased loss of nutrients and/or allow acidic water enriched with aluminum ions to reach aquatic ecosystems.

BIOLOGICAL EFFECTS ON SOILS

Dr. A. J. Francis
Discussion Leader

Some of the key soil microbiological processes that might be most influenced by acid precipitation are given below:

1. Rate of organic matter decomposition
2. Nitrogen transformations
 - a. ammonifications
 - b. nitrification (autotrophic and heterotrophic processes)
 - c. denitrification
 - d. nitrogen fixation (symbiotic and non-symbiotic)
3. Mycorrhizal associations
4. Microbial population distributions
5. Soil enzymatic activities
6. General rhizosphere effects - changes in nutrient levels and organic matter near roots
7. Phosphorus and sulfur transformations
8. Survival and productivity of pathogenic organisms.

In general, productivity of natural ecosystems is limited by organic matter decomposition rates and nitrogen availability. Acidification of soil samples to pH 4.3 inhibited organic matter decomposition markedly over the 24 day test period in which normal rates of ammonification and nitrification were inhibited in soils adjusted to pH 4.3. The increased acidity did not kill these nitrogen transformation organisms but acidity inhibited their activity. Moreover, the change in pH may have only reduced the availability of essential nutrients below the threshold for activity.

Nitrate reduction was inhibited in agricultural soils if the pH was brought to either 5.2 or 3.4 as compared with soil brought to pH 7.0. If nitrate reduction is inhibited by autotrophs the concentration of nitrates may be reduced drastically. Heterotrophic organisms are not effective at low nitrate concentrations.

Denitrification or the reduction of nitrate to elemental nitrogen occurs anaerobically. With an increase in acidity there was an increase in N_2O production but the conversion from N_2O was inhibited. These laboratory results must be confirmed in forest and natural soils. The results suggest that anaerobic micro-organisms can reduce NO_3^- to the level of N_2O but not to N_2 in the presence of excess acidity.

Rates of nitrogen fixation were very low between pH 3.5 and 4.5 with aerobic bacteria. The inhibition by acidity was the same in samples with and without glucose and/or ethylene additions. Anaerobic nitrogen fixation exhibited the same pH response. Moreover, if the natural microbial populations were taken from various soils and grown in various media, populations from neutral soils had higher fixation rates. At neutral pH levels, nitrifying bacteria grew faster and attained higher population densities than did populations from more acid soils.

Two enzymes were described: Dehydrogenase and Urease. In general, dehydrogenase activity increased with an increase in pH up to pH 7.5. However, the enzyme decreased in activity with an increase in soil incubation up to 180 days. In contrast, urease activity increased with an increase in pH but there was no change in enzyme activity over the 180 day test period.

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IMPACTS OF ACID PRECIPITATION ON CROPS

Dr. Jay S. Jacobson
Discussion Leader

Contribution of Dr. David Weber

Experiments at Corvallis, Oregon, at the EPA experimental farm

Experiments with Radish. In 1976, radish plants (a variety sensitive to SO_2) were exposed to simulated acid rain at pH levels of 3.0, 3.5, 4.0, and 5.7 for 3 times per week for 1.5 hr each. Half of the plants remained unwashed after the rainfall treatment while the other half received an application of simulated rain at pH 5.7. Plants exposed to pH 3.0 simulated rain had average root dry weights of only 0.5 g while plants exposed to pH 5.7 had dry weights of 1.3 grams. No significant difference in dry weight was observed between plants exposed to pH 3.0 and 3.5. In fact, the top growth was slightly greater at the lower pH levels. Results of additional experiments showed that there was no reduction in root growth if simulated rain was not applied to the foliage.

The ozone concentration was 0.08 ppm while concentrations of 0.9, 0.6, and 0.3 SO_2 were used. Simulated rainfalls of 5.7, 4.0, 3.5, and 3.0 were applied for 1.5 hr, 3 times per week.

The SO_2 fumigation levels all depressed the fresh weight of radish roots. Application of rainfalls of pH 5.7, 4.0, and 3.5 in the presence of gases had a slightly stimulatory effect compared with treatments with gases only. However, application of pH 3.0 rain in the presence of the gas treatments decreased yields more than in the presence of the gases alone. Except at the lowest pH level the presence of H_2SO_4 and SO_2 were antagonistic. The presence of one sulfur component compensated for the injury inflicted by the other.

Experiments with Alfalfa. Experiments with alfalfa were also performed. Plants were injured if exposed to SO_2 from 0.3 to 0.9 ppm for 1.5 hours daily. Exposure to simulated rain at pH levels from 5.7 to 3.5 (1.5 hr; 3 days per wk) had no effect on growth. However, if plants were exposed to rain of pH 3.0 some injury occurred.

Experiments with onion. Similar results are present with onions. Little injury was evident when plants were exposed to simulated rain of pH 3.0. Exposure to sulfur dioxide decreased the fresh weight of onion bulbs. The highest concentration of SO_2 , the lower the yield. Concomitant with these decreases in yield, the amount of leaf injury increased proportionally to the SO_2 concentration.

Contribution of Lance Evans

In most of the plant species that we have studied, most initial lesions occurred near particular leaf surface structures. In most plant species studied about 75% of all lesions developed near veins. Moreover, lesions originated in epidermis adjacent to trichomes 75%, stomata 20%, and areas not associated with either trichomes or stomata: 5%, respectively. It is evident therefore, that lesions produced by simulated acid rain preferentially affect the leaf epidermis near trichomes, stomata, and vascular tissues.

Leaf sensitivity vs. development. In experiments to view relative sensitivity versus age of first trifoliate leaflets of *P. vulgaris*, plants were exposed to three daily, 6-min exposures to sulfate acid rain, pH 2.7 (Evans, Gmur, and Da Costa, 1977). The density of lesions is low in very young leaves (before the maximum rate of leaf expansion). The curve of lesion density is very similar to the curve of total leaflet area. Densities of stomata and trichomes were very high in young leaflets (10-day-old plants) but decreased to very low levels before the maximum rate of leaflet expansion (14-day-old plants). The leaflet stage with the greatest density of both stomata and trichomes was not the age of maximum sensitivity to simulated acid rain. A difference in sensitivity during leaf development is also present in soybeans. Foliage of soybeans exhibited lesions on about 6 to 7% of the leaf surface after 6 daily exposures to simulated rain of pH 2.7 (Figure 4). Exposure to rainfalls of pH 2.9 produced lesions on about 5% of the leaf surface. In general, younger soybean leaves were more sensitive than fully expanded leaves. Percent leaf area injured was greater after four rainfalls than six rainfalls because the leaves became less responsive to acid rain as leaf expansion continued. In this manner, the number of lesions per leaflet did not increase significantly after day 4 but leaflet area increased markedly.

Crop Yield Experiment. A long-term experiment was performed to determine the several yield parameters on soybean. Plants were exposed to simulated rain of pH levels 5.6, 3.1, and 2.5 for 10 min day⁻¹, 5 days wk⁻¹. The plants were 14 days old when rainfalls began. Rainfalls stopped on day 128 and plants were harvested 5 days later. Forty-eight plants per treatment were used to reduce the level of error. Percent yield reductions and confidence intervals are shown in Table 2. At all parameters measured the yield reduction differences between plants at 5.7 and 2.5 were significant at the 0.001 confidence level. Plants exposed to pH 5.7 had significantly higher stem mass, leaf mass, pod number, seed number, and total seed mass than at pH 3.1. However, seed mass at pH 3.1 was significantly higher than at pH 5.7. It should be noted that confidence limits of 0.001 can be obtained with only 7% difference in yield with 48 plants per treatment. These results show that long term exposure to simulated rain of pH 3.1 reduced the plant biomass of soybean but it did not reduce the seed yield. Exposure of plants to simulated rain of pH 2.5 reduced all experimental parameters measured compared with rain of pH 5.7.

Contribution of Kenneth Reed

Much is known about the physiology and the agricultural productivity of soybeans. Several useful mathematical models have been produced in order to help produce a unified concept of soybean growth, development, and productivity under a variety of environmental conditions. In order to understand (1) how environmental stresses may effect these parameters and (2) the impacts that acid rain might have as an environmental stress, experiments should be designed to understand these relationships.

One type of model is a high resolution mechanistic model. This type of model determines soybean nutrient translocation and accumulation in various plant parts in relation to the mass of the parts.

The eventual aim of this scientific approach is to proceed through the following levels: chemical, plant, immediate environment within the surroundings, hectare, spatial (topographic areas), and economics.

Figure 4. Relationship between percent leaf area injured and number of daily exposures (20 min each) of simulated rain on middle leaflets of first trifoliate leaves of soybean (*Glycine max*). Diamonds, squares, triangles, and circles represent injury after exposure to simulated rain of pH 2.7, 2.9, 3.1, and 3.4, respectively.

Table 2

Percent reduction in the mass of soybean plant parts of plants exposed to simulated acid rain.

Plant portion	Comparison	Percent Yield Reduction		Percent Yield Reduction	
Stem mass	5.7 $\gg^{b/}$ 3.1	(15)	5.7	2.5	(29)
Leaf mass	5.7 $\gg$ 3.1	(6)	5.7	2.5	(14)
Pod number	5.7 $\gg$ 3.1	(10)	5.7	2.5	(12)
Seed number	5.7 $>$ 3.1	(7)	5.7	2.5	(12)
Seed mass	5.7 $\ll$ 3.1	(-11)	5.7	2.5	(11)
Pod and seed mass	5.7 = 3.1	(5)	5.7	2.5	(15)
Total shoot mass	5.7 $>$ 3.1	(4)	5.7	2.5	(18)

a/ Soybean plants were exposed to simulated rain of either 5.7, 3.1, or 2.5 for 10 min day⁻¹ for 5 days week⁻¹. Fourteen-day-old plants were exposed to 7% rainfalls over a time period of 112 days.

b/ $\gg$ = .001 confidence interval

$>$ = .05 confidence interval

= = not significant

N = 48 plants per treatment

Contribution of Jay S. Jacobson

Four experimental approaches to the study of effects of acidic rain on plants have been performed at the Boyce Thompson Institute between 1974 and 1979. Greenhouse-grown plants were exposed to simulated rain of different acidities, durations and frequencies of exposure, and rainfall intensities to determine dose-response relationships for the development of foliar lesions. These results have been reported previously (J.S. Jacobson and P. Van Leuken), 1977). Following these tests, greenhouse-grown lettuce plants were exposed to simulated rain of different acidities, sulfate, and nitrate concentrations to determine effects on growth and nutrient content. A field experiment then was carried out to evaluate the combined effects of acidic rain and ambient ozone on the growth, yield, and quality of soybeans. Plants were grown in field chambers with and without filtration of air to remove ambient ozone, with covers on the chambers to exclude ambient rain, and with application of simulated rain at three acidities. Recently, another field experiment was performed with bush beans grown in the field but without chambers. The crop was exposed to ambient acidic rain and simulated rain at three acidities and measures of growth, yield, and quality were taken to determine effects on the market value of the crop.

We have concluded from these studies that: (1) further refinements of methods and experimental approaches are necessary in order to provide a quantitative evaluation of the effects of acidic rain on agricultural crops; (2) characteristics of rain events that are of importance in addition to rain composition are duration and frequency of events, time between events, and intensity of rainfall; (3) the sulfate and nitrate content of rain may have an important influence on growth and development of some plant species and the supply of these nutrients may counter the effects of acidity; and (4) the effects of acidic rain on plants in the eastern U.S. may differ depending on the intensity of exposure to atmospheric ozone.

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IMPACTS OF ACID PRECIPITATION ON FOREST ECOSYSTEMS

John S. Eaton
Discussion Leader

Contribution of John S. Eaton

Watershed ecosystem studies have become a valuable tool in furthering our understanding of natural ecosystems and the effect of man caused, or other perturbation on these ecosystems. The nature of these studies is to show the integrated effect of the various biotic and abiotic factors on the ecosystem along with the resultant system interactions.

The Hubbard Brook ecosystem is a cool, temperate hardwood forest ecosystem in eastern North America. The net primary productivity of this forest both above and below ground was $1106 \text{ g/m}^2\text{-yr}$, a reduction of 18% (Whittaker et al., 1974). This period of sharply reduced productivity was a period of increasing acidity in precipitation. However, this was also accompanied by a period of drought. These and other environmental factors complicate the cause and affect analysis in ecosystem studies and have made it impossible to show any direct effect between acid precipitation and reduced forest productivity (Cogbill, 1977). This, in turn, points to the additional need for studies of the synergistic effect that acid precipitation may have on various biotic and abiotic factors within the ecosystem (e.g., availability of soil nutrients, plant pathogens, plant metabolism, etc.) which can affect forest productivity.

The measurement of rain above a forest canopy shows that the ionic concentration is lower than that of the throughfall water below the canopy. The forest canopy is an effective collector of atmospheric particulates, aerosols and some gases. The increase in the ionic strength of the rain as it passes through the forest canopy is due to the washing off of impacted materials and the leaching of materials from the leaves. A notable exception to this rule in a northern hardwood forest is the high concentration of H^+ in ambient rainfall compared with throughfall water (Eaton et al., 1973). It is thought that hydrogen ions are exchanged for other components within the leaves and that neutralization occurs due to the impacted materials on the canopy. The net effect is that, during the summer months, the precipitation which reaches the forest floor may be significantly changed both from the standpoint of ionic strength and pH from that which fell on the forest canopy. However, the acidity of precipitation during the summer months is generally greater than that of the winter. For example, our lowest recorded pH's occurred during two rain events in August of 1977 and 1978 which had pH levels of 2.85 and 2.80, respectively. This coupled with the fact that the plants are in their active growing period during this time would point to the increased probability of deleterious effects from acid precipitation.

During the winter months at Hubbard Brook, there is little foliage in the forest canopy and, therefore, there is a greatly reduced reactive surface. Also, the majority of the precipitation occurs as snow which passes through the forest canopy with little or no change in its ionic strength and pH. Precipitation which occurs during the winter months is generally less acid and typically leaves the ecosystem rapidly during the spring snow-melt period. This rapid passage from the ecosystem reduces the opportunity for reactions between the precipitation and system through which it is passing. However, it may carry the acid precipitation problem into stream or lake ecosystems beyond.

Contribution of William Freedman

The possible effects of acid precipitation on forest ecosystems may be divided into two principal categories. They are: (1) acute toxicity (that results in a decrease in growth or death of individuals) and (2) chronic toxicity (that results in decreased growth, vigor, and reproduction that might result in death on a long-term basis).

These two principal categories may not be evident. Researchers have approached the problem somewhat differently. They have looked for:

1. changes in forest productivity.
2. changes in the relative species composition within an ecosystem.
These changes may be due to differences in the relative sensitivities of various organisms to acid rain.
3. changes in nutrient cycling that may result in the loss of edificator plants.
 - a. the loss of bryophytes may decrease the quantity of nutrients tied up on a short-term basis.
 - b. a decrease in callons held by canopy due to an increase in foliar leaching must be compensated for by an increase in root absorption of these nutrients.
4. changes in nutrient cycling in soils due to long-term acidification.
5. changes in plant pathogen numbers and degree of plant injury that may result. This effect may be direct or indirect because of competition for nutrients among microorganisms.
6. alteration in ecosystem structure by inputs of nitrogen and sulfur that may act as fertilizer.

Contribution of John Aber

Present research results suggest that acidity in precipitation may have many effects on forest ecosystems. They are:

1. Direct effects of an increase in proton concentration on soils.
 - a. decrease in base saturation
 - b. decrease in cation availability
 - c. increased solubility of iron, aluminum, and heavy metals
 - d. decreased availability of phosphates.
2. Indirect effects of an increase in proton concentrations in soils.
 - a. decreased biotic decomposition rates
 - b. decreased root growth
3. Increased nitrogen input
 - a. availability of nitrogen
 - b. effects on biotic decomposition rates
4. Increased sulfur input
 - a. availability of sulfur
 - b. interaction of sulfur compounds with other soil nutrients.

If there is a significant increase in nitrogen input and availability that results from acid precipitation, what might the effects be? Computer models may indicate some long-term changes in biota within a forest or natural ecosystem. A model has been exercised to predict changes in:

- i. basal area of trees as a function of time.
- ii. forest floor biomass as a function of time.
- iii. nitrogen availability as a function of time.
- iv. nitrifying bacteria.

Over an average of 120 to 200 years an increase in nitrogen availability from 40 to 100 kg/ha/yr would increase the forest biomass from 200 to 425 tons/hectare at 2500 degree days while the same nitrogen available change would increase the biomass from 100 to 550 tons/hectare at 3000 degree days.

If the amount of leaf production per year were plotted over the same change in nitrogen availability range the rate of increase is very gradual at 2500 degree days. However, a marked increase in leaf production occurs at 3000 degree days.

Contribution of Jeff Lee

Seed germination and seedling establishment are important processes of forest regeneration of acid rain as an effect on forest ecosystems. Moreover, acidity may have notable effects on this vulnerable stage in the life cycle.

Seeds and young seedlings were exposed to rain three times per week for a total of one inch of water per week. The pH levels of the simulated rain were 5.7, 4.0, 3.5, and 3.0. The germination rates of various forest tree species differ. The rates of germination are not affected by the pH levels used. Moreover, differences in seedling shoot mass did not appear significant either during the time period tested. Although there were no differences in root mass among the various treatments primary roots were sensitive to acidic conditions.

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STATE OF KNOWLEDGE AND RESEARCH PRIORITIES

The purpose of this session was to pose various questions for the workshop and to enable participants to see areas of both consensus and diversity of opinion. During this session participants were asked to evaluate the levels of knowledge in specific areas to help make decisions as to what is and isn't important as far as environmental research is concerned, and to rank research priorities based upon the levels of knowledge and the anticipated needs for more research.

To determine the level of knowledge on specific topics the participants were asked to respond to a series of questions by answering "yes," "no," or "unknown." Table 3 shows a listing of the questions posed at the session and the voting that occurred. It is evident that there is little difference in wording among some of the questions posed. It was difficult to find the most appropriate wordings for some questions. There seemed to be little need to retain some questions in this report because they were similar to other questions. However to be complete, all questions and responses are given in chronological order. A careful reading of each question is necessary.

Many participants indicated that acid rain, at present levels in nature or in artificial systems, causes plant injury (question #1). The number of participants that responded "yes" to question #1 was greater than the number that responded "no." This question was restated with the first word changed to "can" (question #4). More participants responded "yes" and nobody responded "no." A majority stated that acid rain injures plants in terms of reproduction (question #2) but the levels of significance of this injury is unknown (question #3). None thought the affects of acid rain are due to a change in the pH inside leaves (question #30).

Acid rain was thought, by some participants, to injure plant tissues in terms of plant metabolism (question #5) but more research in this area (question #6) is necessary to understand the total impacts. Although acid rain was thought by some to cause an alteration in plant tissue in terms of food and fiber production (question #7) there was no consensus of opinion as to which crops (question #16) or which stages in the life cycle (question #21) would be most affected. However, a significant number thought that pollination and fertilization are likely to be affected by acidity (question #23).

Most participants indicated that crops are more likely to be affected by direct contact with acid rain than by changes in soils (question #15). Although acidic solutions may accelerate nutrient leaching (Wood and Bormann, 1974; Fairfax and Lepp, 1975), there was no commitment to whether leaching of nutrients from foliage was accelerated to such a degree that might affect growth, development, and yield. (question #20). On the leaf surface, acid rain was thought to alter microfloral populations (question #26) but only two thought that acidity was sufficient to affect the incidence of plant diseases and most participants didn't know (question #25). Moreover, the acid rain whether or not affects the incidence of plant disease (question #27) is almost completely unknown. About half of the participants thought acid rain can alter stomatal function (question #28).

The components within acid rain were rated on their possible beneficial effects to plants. Most participants thought that crops could benefit from supplies of nitrate (question #18) and sulfate (question #17). However, only two people thought that hydrogen ions from acid rain could benefit crops (question #19) and most didn't know. Therefore, many participants thought

that acid rain has some demonstrated positive effects (question #12). Many biological influences may alter the responses of plants to acid rain (question #24).

All participants stated that long-term research efforts are necessary to evaluate the effects of acid rain on natural ecosystems (question #13). Moreover, artificial ecosystems may help us understand the effects as well (question #14). For the present, all participants agreed that there are alterations in terrestrial ecosystems from acid rain (question #10a) but none was convinced that the effects are harmful (question #10b). Most participants thought that the effects of acid rain on grassland ecosystems were low (question #34).

Toward the beginning of the session only one person thought that acid rain has significantly affected the pH of soils (question #22). However, later many people stated that acid rain has affected the pH of soils (questions #32 & 33). When participants were asked if acid rain can/does alter soils to such a degree that plants are affected, ten positive responses were obtained (question #8). However, we asked if acid rain has already altered soils to such a degree that plants are affected, only one person responded positively (question #9).

Lists of research priorities on the effects of acid precipitation on crops, soils, and terrestrial ecosystems are shown in Tables 4, 5, and 6. These tables indicate the most important research priorities ranked by the participants. These tables are the same as tables i, ii, and iii, respectively given in the executive summary.

The ranking of research priorities was done in two ways. For the sections that deal with crops (Table 4) and terrestrial ecosystems (Table 6) participants were asked to list their five priority choices. The number of positive responses is the total number of times that a priority was listed among the 5 highest priorities by the 26 participants. Since the group expressed the idea that the statements taken from a "National Program for Assessing the Problem of Atmospheric Deposition" represented all known major priorities with regard to soils, participants were asked to place the statements in their order of importance. Rankings were assigned point scores from 1-10, the highest scores were given to the most important statement (Table 5). For example, if a person marked a statement as first priority, that priority received a total of 10 points. After all scores were added the total scores were divided by the total number of participants.

The diversity of research priorities mentioned reflects the large diversity in the backgrounds of the participants. In this way, the process of attaining a meaningful opinion from the participants was a very difficult process and this process was met with only limited success.

Table 3

State of Knowledge of the Effects of Acid Rain on Vegetation, Soils, and Terrestrial Ecosystems: A Poll of Participants using Selected Questions.

Question

1. Does acid rain, at ambient levels or in artificial systems that simulate ambient levels, cause injury to plant tissues?	Yes: 12 No: 4 Unknown: 9
2. Does acid rain cause injury to plant tissues in terms of plant reproduction?	Yes: 13 No: 0 Unknown: 12
3. Does acid rain cause injury to plant tissue and is such injury significant to plant reproduction?	Yes: 0 No: 0 Unknown: 26
4. Can acid rain cause injury to plant tissues at ambient levels or in artificial systems that simulate ambient levels?	Yes: 19 No: 0 Unknown: 9
5. Does acid rain cause injury to plant tissues in terms of plant metabolism?	Yes: 7 No: 0 Unknown: 18
6. Are investigations on acid rain effects in terms of plant metabolism a fruitful area of research in the future?	Yes: 26 No: 0 Unknown: 3
7. Does acid rain cause an alteration in plant tissue in terms of food and fiber production?	Yes: 9 No: 2 Unknown: 18
8. Can and/or does acid rain alter soils to such a degree that plants are affected?	Yes: 10 No: 0 Unknown: 18
9. Has acid rain already altered the soil to such a degree that plants are affected?	Yes: 1 No: 9 Unknown: 15
10a. Do we agree that there are alterations to terrestrial ecosystems from acid precipitation?	Yes: 26 No: 0
10b. Are there demonstrated harmful effects on terrestrial ecosystems?	Yes: 0 No: 6 Unknown: 9
11. What about artificial situations, are there demonstrated harmful effects on vegetation which includes crops?	Yes: 26 No: 0 Unknown: 0

Table 3 cont.

Question

12. Are there any demonstrated positive effects of acid precipitation?	Yes: 13 No: 0 Unknown: 7
13. Is long-term research necessary to evaluate effects in natural ecosystems?	Yes: 25 No: 0 Unknown: 0
14. Should we pursue this line of research in artificial ecosystems?	Yes: 26 No: 0
15. Are crops more likely to be affected by components of rain through changes in soils or by direct contact with rain?	Soils: 3 Dir. Contact: 16
16. Which crop plants in the following categories are most likely to be affected by acidity of rain?	Vegetables: 3 Grains: 1 Fruits: 2 Other/unknown: 18
17. Do any crops benefit from supplies of sulfate in rain?	Yes: 19 No: 0 Unknown: 1
18. Do any crops benefit from supplies of nitrate?	Yes: 21 No: 0 Unknown: 1
19. Do any crops benefit from supplies of protons or H ions from rain?	Yes: 2 No: 0 Unknown: 22
20. Is leaching of nutrients from foliage accelerated to a sufficient degree that affect growth, development, and yield are affected?	Yes: 0 No: 1 Unknown: 20
21. Which stage of growth is most vulnerable to acidity in rain?	Seedling: 4 Early growth: 3 Flowering: 1 Fruit set: 2 Fruit matur.: 0 Unknown/uncommit.: all others
22. Do you think acid rain has significantly affected pH of soil, etc.?	Yes: 1 No: 3 Unknown: 17

Table 3 cont.

Question	
23. Are pollination and fertilization likely to be affected by acidity?	Yes: 13 No: 3 Unknown: not determined
24. Do biological factors influence plant response?	Yes: 16 No: 0 Unknown: 1
25. Does acidity of rain alter microfloral populations on leaf surfaces sufficiently to affect the incidence of plant diseases?	Yes: 2 No: 0 Unknown: 20
26. Restated: Does acidity of rain alter microfloral populations on leaf surfaces?	Yes: 11 No: 0 Unknown: 10
27. Does acidity of rain affect the incidence of plant diseases?	Yes: 0 No: 0 Unknown: all
28. Does acidity of rain alter stomatal function?	Yes: 9 No: 0
29. Does repeated exposure to acid rain alter crop response to gaseous pollutants such as ozone or SO ₂ ?	Yes: 12 No: 0 Unknown: 10
30. Does acidic rain change the pH inside the leaf?	Yes: 0 No: 3 Unknown: 16
31. Does disposition of particulate matter on foliage alter the effects of acid rain on crops?	Yes: 14 No: 0 Unknown: 2
32. Does anyone believe that acid rain has affected the pH of soils?	Yes: 13 No/Unknown: cannot determine from tape
33. Do you think that the acidity in rain has significantly altered the pH of the soil solution?	Yes: 10 No: 0 Unknown: 2
34. How many participants would agree that the priority in grassland ecosystem research with respect to acid rain is low?	Yes: 13 No: 0 Unknown: 3

Table 4

List of Priorities on Effects of Acid Precipitation on Crops

Rank	Research Area	Number of Responses ^{a/}
1.	Crop sensitivity (yields)	7
2.	Interactions with other pollutants including particulates	5
3.	Dose-effects studies	4
4.	Identification of crucial sensitive life cycle stages	4
5.	Effects of pollination/pollen viability	4
6.	Physiological responses/stomatal function	3
7.	Effects on plant pathogens	3
8.	Direct and indirect effects	3
9.	pH effects within cells	2
10.	Metabolic effects	2
11.	Sulfate concentrations and effects within cells	1
12.	Lime compensation experiments	1
13.	Trace element deficiency development	1
14.	Effects on storage problems	1
15.	Identification of special regional problems	1
16.	Effects on N-fixation	1
17.	Economic impacts	1
18.	Hidden injury i.e., chronic effects	1
19.	Rhizosphere effects	1
20.	Nutrient budget impacts	1
21.	Seed germination	1
22.	Standardized methods/microcosms, etc.	1

^{a/}The participants listed three major priorities of research on the effects of acid rain on crops. The number of responses in each category is given.

Table 5

List of Priorities on Effects of Acid Precipitation on Soils

Rank	Research Area ^{1/}	Average Score ^{2/}
1.	Effects of soil acidification on leaching of exchangeable plant nutrients, such as Ca, Mg, K, Fe, and Mn.	
	Effects of acidification on the rate of weathering of soil minerals.	7.3
2.	Effects of simulated acid rain on leaching losses of Al from soils.	6.5
3.	Effects of acidification on the availability of P to plants and the availability of phytotoxic elements such as Al.	6.0
4.	Natural soil formation processes in humid regions tend toward acidification. How does acid precipitation affect this process.	6.0
5.	Effects of acidification on soil microbiological processes such as N fixation and breakdown of residues. The following processes may be influenced by soil acidification:	
	a) Nitrogen fixation by <u>Rhizobium</u> <u>bacteria</u> on legumes and by <u>Azotobacter</u>	
	b) Mineralization of N from forest floors	
	c) Nitrification of ammonium compounds	
	d) Overall decay rates of forest floor material and, therefore, the rate of availability of stored nutrients.	5.6
6.	Determine the factors that establish susceptibility of soils to acidification.	5.6
7.	Determine the effects of acid precipitation on largely uncultivated areas that have soils that are poorly buffered and may be most susceptible, i.e., forest and wilderness areas of the United States and Canada.	4.4

Table 5 cont.

8. Determine the effects of heavy metal deposition associated with acid precipitation. 4.2

9. Determine the significance of quantities of plant nutrients such as N and S that are being added to soil by dry deposition and precipitation. In some ecosystems these inputs may be important in the maintenance of the nutrient budget. 4.1

1/The statements taken from "A National Program for assessing the Problem of Atmospheric Deposition (Acid Rain), a report to the Council on Environmental Quality by NADP (NC-141)" were rephrased in the form of research priorities.

2/Participants were asked to rank the statements from 10 (highest rank) to 1 (lowest rank). Average scores represent the mean value obtained when the total values from all ballots were divided by the total number of ballots.

Table 6

List of Research Priorities on Effects of Acid Precipitation
on Terrestrial Ecosystems

Rank	Research Area	Number of Responses ^{a/}
1.	Interaction with toxic elements (Al, Fe, Mn)	9
2.	Effects on nutrient cycling	9
3.	Effects on nitrogen cycle	8
4.	Long-term studies on forest plots (with other interactive factors applied)	7
5.	Studies on species and regional sensitivities	7
6.	Litter decomposition	7
7.	Identification of sensitive soils	6
8.	Studies of forest productivity (growth analysis)	5
9.	Studies of sulfur compounds in soils	4
10.	Pollination of plants	3
11.	Refinement of methods for measuring forest production sensitive to a 5% change in productivity	3
12.	Soil microorganisms	3
13.	Aquatic ecosystems	3
14.	Identification of indicator species	2
15.	Reproduction of forest species	2
16.	Leaf surface processes	2
17.	Ecosystem model development and refinement	2
18.	Use of microcosm and greenhouse studies	2
19.	Effect of foliar leaching on nutrient status of an ecosystem	2
20.	Interaction with biota agents	2

Table 6 cont.

21. Effects on soil organic matter	1
22. Development of measurable dose parameters to determine effects	1
23. Effects on cation exchange capacity	1
24. Effects on plant pathogens	1
25. Effects on soils	1
26. Studies on dry deposition effects	1
27. Controlled field exposures - measurements and evaluation of experimental results	1
28. Effects of mycorrhiza	1
29. Interactions with other pollutants	1
30. Interaction effects with sulfurous SO ₂ on leaves	1
31. Gradient deposition studies	1
32. Tree physiology	1
33. Effects on tundra vegetation	1

^a/The participants listed five major priorities of research on the effects of acid rain on terrestrial ecosystems. The number of responses in each category is given.

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