WORKSHOP REPORT on Acid Precipitation and the Forest Ecosystem

USDA FOREST SERVICE GENERAL TECHNICAL REPORT NE-26
1976

NORTHEASTERN FOREST EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
6816 MARKET STREET, UPPER DARBY, PA. 19082

FOREWORD

This is a report on the workshop following the First International Symposium on Acid Precipitation and the Forest Ecosystem, held at The Ohio State University, Columbus, Ohio, on 15-16 May 1975. The findings and recommendations offered here are the consensus of Workshop participants and are not to be considered as official positions of the USDA Forest Service, The Ohio State University, or the National Science Foundation.

The Symposium and the Workshop were sponsored by the Northeastern Forest Experiment Station, USDA Forest Service; the Atmospheric Sciences Program of The Ohio State University; and the National Science Foundation, Grant No. DES 75-13749.

WORKSHOP REPORT on Acid Precipitation and the Forest Ecosystem

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INTRODUCTION

THE FIRST International Symposium on Acid Precipitation and the Forest Ecosystem provided the first world-wide forum devoted to consideration of acid precipitation and forestry problems. The Symposium brought together experts from diverse fields of the physical and biological sciences to discuss their research and their concerns about a potentially serious environmental problem. A Workshop, organized as a follow-up to the Symposium, benefited greatly from participation by more than 60 international scientists. This is a report on that Workshop.

Five discussion panels were formed to consider (1) Atmospheric Emissions, Transport, Transformation, and Removal; (2) Effects on Aquatic Systems; (3) Effects on Forest Soils; (4) Effects on Forest Vegetation; and (5) Energy-Related Issues. Two co-chairmen in each problem area were responsible for organizing, developing, and reporting the findings of their respective panels. Many of the panel members on energy-related issues also participated in other panels to bring still broader perspectives to the relationship between acid precipitation effects on the forest ecosystem and energy.

This report identifies the nature, extent and dimensions of the problems associated with acid precipitation. The recommendations contained here should serve as a guide for research by scientists and for program-planning by academic, industrial, government, and public-interest groups.

Leon S. Dochinger
principal plant pathologist
USDA Forest Service
Northeastern Forest Experiment Station
Delaware, OH 43015

Thomas A. Seliga, director
Atmospheric Sciences Program
The Ohio State University
Columbus, OH 43210

ACID PRECIPITATION: AN ENERGY-RELATED ENVIRONMENTAL PROBLEM

THE ENERGY PROBLEMS of the world relate to nearly every aspect of life. Of great importance is whether we have or are developing the knowledge needed to deal with these problems in the most efficient, economic, and environmentally beneficial ways. The effects of acid precipitation on the earth's ecosystem are areas worth immediate attention.

The relationship of acid precipitation to energy production from fossil fuels is complex (fig. 1). Further, there are significant unanswered questions about the ecosystem and its ability to regenerate resources such as agricultural crops and forest vegetation under the stress of acid precipitation.

In Sweden and Norway the acidity of rain and snowfall has increased to the point that some streams and lakes have become toxic to fish and other organisms. Further studies have suggested that forest growth in these countries has been adversely affected. The higher acidity is associated primarily with the sulfate and nitrate contents of the precipitation in Scandinavia. The sources of these compounds appear to be mostly anthropogenic and have been traced to sites as remote as 2,000 kilometers. This kind of observation has caused concern in areas of the world that are generally downwind from heavily urbanized and industrialized regions. Potentially impacted areas include the eastern United States and Canada and portions of the southwestern United States.

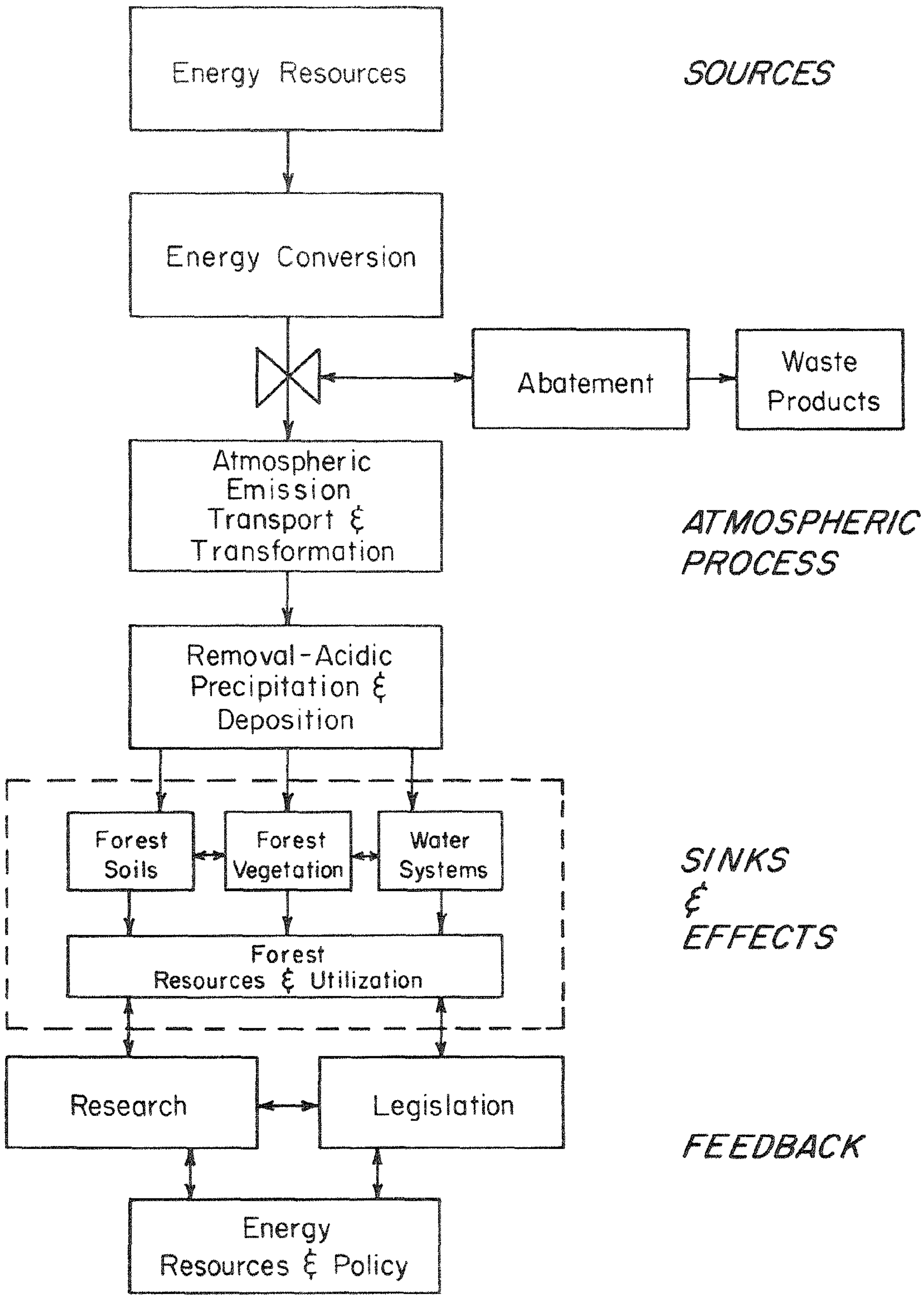
Oxides of sulfur are produced by the oxidation of sulfur contained in fuels and ores when they are combusted or smelted. The higher the sulfur content, the greater the amount of sulfur oxides emitted into the atmosphere. Major producers of sulfur oxides are power plants (both public utilities and those that provide energy for various industries); copper, lead, and zinc smelters; steel plants; and urban areas where coal and fuel oil and sulfur-containing gas are used for space heating. Automobiles may also be a source of sulfur oxides, but their contribution, except perhaps in urban regions, is relatively minor compared to that of industrial processes. Natural sources of important sulfur-bearing compounds include volcanoes, fresh and salt waters, and biological reactions.

Oxides of nitrogen are formed during combustion at high temperatures. Significant sources of NO_x are power plants, automobile exhaust, smelting operations, and space heating. However, the estimate of natural vs. anthropogenic emissions is overwhelmingly toward natural sources, which are primarily due to biological reactions.

Acidifying materials emitted into the atmosphere are subjected to many conditions. When they and other potentially harmful or beneficial compounds are removed from the atmosphere, the forest ecosystem may be affected. Because of this relationship and the possible importance and future implication of acid precipitation on the forest environment, the First International Symposium on Acid Precipitation and the Forest Ecosystem was held in May 1975 at The Ohio State University to assess present knowledge on the subject.

This report presents the findings of a Workshop that was held following the Symposium. The major Workshop recommendations were that (1) more research is needed to evaluate ecological effects and economic impact of changes in the acidity and other chemical properties of precipitation and (2) a network should be established to monitor the chemistry of air and precipitation in rural and urban locations throughout the world.

Figure 1.—The relationship of energy production to acid precipitation.



ATMOSPHERIC EMISSIONS, TRANSPORT, TRANSFORMATION, AND REMOVAL

The increasing acidification of precipitation has added a new dimension to the air-pollution problem — pollution that had been treated largely as a local problem has become a regional one. Also, because of the long-range transport attributed to acidic pollutants, acid precipitation must be considered an international environmental problem.

To determine acid input to the forest ecosystem, a thorough understanding of emissions, chemical and physical transformations, transport, and removal mechanisms is required. Pollutants of various kinds are emitted from both natural and anthropogenic sources. While the emissions are often complex in their chemical makeup, those of greatest concern are SO_2, CO, NO_x, reactive (nonmethane) hydrocarbons (RHC) and particulates. The particulates range from organic to inorganic, from toxic to nontoxic, and over a few orders of magnitude in size. Of greatest concern are the smaller particulates in the size range from 0.3 μm to 3 μm; in addition, chemically toxic particulates such as heavy metals of various sizes may also be important.

While in the atmosphere, air pollutants may react with each other and with natural components of the atmosphere such as water vapor, ammonia, ozone, and other hydrocarbons. Simultaneously, these pollutants are transported by atmospheric motions both horizontally and, to a lesser extent, vertically. Finally, they are removed either by physical encounter with surfaces (dry deposition) or by precipitation (wet removal).

An understanding of atmospheric processes is essential in understanding their role in acid-precipitation-related problems. Furthermore, since the problems are more regional than local, the considerable amount of research on air pollution that has been aimed primarily at local phenomena is not adequate. Further research is required so that the extent to which anthropogenic emissions contribute to acid precipitation can be assessed.

Research Recommendations

I. Emissions

There is an insufficient amount of data on low concentrations (background) of air pollutants. This kind of data is particularly lacking for rural areas, but also is insufficient for locations where the air quality is considered good. Yet, evidence has been accumulating that pollution from industrial and urbanized regions is not necessarily all removed from the atmosphere in the vicinity of the sources, but is often transformed and transported up to thousands of kilometers away. Consequently, data collection must be improved and expanded to monitor low concentrations of pollution in general and acid precipitation in particular.

A. Improve and expand emission inventories of natural and anthropogenic sources of pollutants contributing to acid precipitation and related problems. These inventories should include SO_2, CO, NO_x RHC, and particulates. It is especially desirable to quantify the natural emissions of ammonia, H_2S, and other possible sources of acidity in the atmosphere. Spatial resolution should be at least of the same scale as anthropogenic emissions. Data should be sufficient to define seasonal averages.

B. Both national and international cooperation and standardization are necessary for the exchange of data on emissions and the long-range transport of pollutants. Industry should be encouraged to report on its emissions on a worldwide basis and make its data available to responsible scientific organizations.

II. Transport

Pollutants introduced into the air tend to follow atmospheric motions. This transport is mostly turbulent, exhibiting a distribution of energy over a wide range of scales. At the microscale, in the immediate vicinity of the source, emissions are diluted by four to six orders of magnitude. The remaining concentrations are spread over greater distances. Dispersion of pollutants to regional scales (hundreds of kilometers) seems to be responsible for observations of pollution remote from the sources. Since the atmosphere is in constant motion, once substances enter the atmosphere they can, if not removed, contribute to the global background. Because of the large scales, long time factors, and relatively low concentrations of pollutants, new research efforts will be needed.

A. Establish national and international programs to monitor low concentrations of pollution and acid precipitation in particular.

- Monitoring networks should have adequate resolution over regional scales.
- Monitoring should be long-term and use standardized methods.
- Networks should be established where substantial acidic precipitation exists and where the potential for future degradation is greatest.
- Measurements should include pH, $[H^+]$, SO_2, NO_X, NH_3, $SO_4^=$ Mg, Cl, and acidity of particulates.
- Precipitation chemistry should resolve the strong and weak acid contributions.
- National and international systems of collection and dissemination of data should be established; priority should be given to establishment of a computerized data library for rapid analysis and retrieval.
- Existing institutions such as the land-grant universities, Agricultural Research Service, and USDA Forest Service in the United States should be encouraged to lead the effort in data collection and analysis.

B. Long-range transport models should be developed. These are needed to trace the sources of pollutants and to test theories of transport, transformation, and removal by comparing model results with measurements from monitoring networks. Such models would be useful for predicting future trends in the condition and behavior of the atmosphere.

C. Meterological boundary-layer studies near major pollutant sources and over complex terrain are required. These will provide information on vertical mixing and identify any limitations of the mechanisms used in transport models.

III. Transformations

Atmospheric reactions and chemical kinetics play an important role in the transformation of anthropogenic emissions into acidifying substances. Of particular importance are the rates of conversion of sulfur dioxide to sulfur trioxide, sulfuric acid, and other possible sulfate aerosol precursors. Both gas phase and heterogeneous reactions involving sulfur dioxide and its derivatives and other acidifying emissions such as nitrogen oxides must be evaluated. More research is required to clarify the chemistry operating in the atmosphere, especially that involving sulfur, nitrogen, and chlorine reactants: the role of water vapor, ammonia, and other organic compounds should also be determined.

A. The nature of equilibria between natural raindrops and low concentrations of SO_X and NO_X and the effects of catalysts on the system should receive attention.

B. Laboratory-chamber experiments to study chemical reaction mechanisms generating acid substances under conditions with realistic atmospheric admixtures and realistic ambient concentrations of pollutant species should be performed.

C. Field investigations of the chemistry operating within plumes from individual sources and from multiple source regions should be expanded.

D. Field investigations of the atmospheric chemistry in rural regions should be made and evaluated in terms of known reaction kinetics, transport, and removal mechanisms.

IV. Removal Mechanisms

Removal of pollutants occurs in either dry or wet form. Dry removal results from impaction of the pollutants onto a surface and its retention there. Precipitation involves the water cycle of the atmosphere, in which absorption into hydrometeors occurs either through in-cloud rainout and snowout or through below-cloud washout processes. Understanding these removal mechanisms is essential to determining input to forest ecosystems. Research should help ascertain what the lifetime of pollutants is in the atmosphere, where they are likely to be deposited, and in what form they will be when deposited.

A. Develop techniques for determining the deposition of pollutants over large areas.
B. Perform laboratory and field studies of the aerodynamic processes of the dry removal of gaseous and particulate pollutants in forests. Both the injurious and possible beneficial results of the forest biomass as a pollution sink should be investigated.
C. Evaluate the effectiveness of cloud systems in the removal and redistribution of pollutants.
D. Develop and test theoretical and empirical relations that provide quantitative information about removal processes, including all precipitation phenomena. Results should be applicable to conceptual models relating to effects of atmospheric acidity.

Panel Cochairmen

D. G. Fox
USDA Forest Service
Rocky Mountain Forest & Range Experiment Station
Fort Collins, CO 80521

T. A. Seliga
Atmospheric Sciences Program
The Ohio State University
Columbus, OH 43210

Panel Members

R. Beadle
Division of Biomedical & Environmental Research
U.S. Energy Research and Development Administration
Washington, DC 20545

S. Baruch
Environmental Projects Manager
Edison Electric Institute
New York, NY 10016

M. Benarie
Institut National de Recherche Chimique Appliquee
Centre de Recherche B.P. No. 1
91710 Vert-le-Petit
FRANCE

H. Benedict
SRIe Kennecott
South Pasadena, CA

C. Brosset
Swedish Water & Air Pollution Research Laboratory
Sten Sturegatan 42
S-402 24 Gothenburg 5
SWEDEN

J. G. Calvert
Department of Chemistry
The Ohio State University
Columbus, OH 43210

P. E. Coffee
N.Y.D.E.C.
Division of Air Resources
Albany, NY

H. I. Fuller
U K Institute of Petroleum
ESSO Petroleum Ltd.
Abingdon, ENGLAND

B. Manowitz
Brookhaven National Laboratory
Upton, NY 11973

J. M. Miller
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
Silver Spring, MD 20910

J. Nord
Norwegian Meterological Institute
Blendern
Oslo 3
NORWAY

B. Ottar
Norwegian Institute for Air Research
Royal Norwegian Council for Scientific and Industrial Research
P.O. Box 115
N-2007 Kjeller
NORWAY

H. S. Sandhu
Alberta Department of Environment
Edmonton, Alberta
CANADA

R. G. Semonin
Illinois State Water Survey
Urbana, IL 61801

P. W. Summers
Atmospheric Dispersion Division
Air Quality and Inter-Environmental Research Branch
Environment Canada
Downsview, Ontario
CANADA

H. J. Viebrock
Meteorology Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

E. G. Walther
Charles F. Kettering Foundation, Suite 300
Dayton, OH 45429

H. A. Wiebe
Atmospheric Environmental Service
Department of the Environment
Downsview, Ontario
CANADA

EFFECTS ON AQUATIC SYSTEMS

An important consequence of acid precipitation falling on the landscape is the acidification of lakes, ponds, and streams. Hundreds, possibly thousands, of lakes and streams in Sweden, Norway, southeastern Canada, and the northeastern United States have become so acid that dramatic changes in water habitats have been observed. For example, large areas of western, southern, and eastern Norway have experienced losses to salmon fisheries that amount to tens of millions of dollars annually. Studies in the United States indicate that fish populations have been adversely affected in 75 percent of the high-elevation lakes of the Adirondack Mountains of New York State and that many lakes and streams can no longer support salmanoid fishes.

In Canada near Sudbury, Ontario, where more than 3 percent of the world's estimated anthropogenic sulfur emissions are released into the atmosphere, acidification of nearby lakes has resulted, followed by the extinction of many fish and insect species and loss of algal populations. Adverse effects of the strong acids (sulfuric, nitric, and hydrochloric) in precipitation on bacteria, phytoplankton, zooplankton, macrophytes, invertebrates, and salamanders have also been observed in many watersheds.

Since acquatic habitats appear to be highly sensitive to acid precipitation and other atmospherically derived substances, research programs are required to further determine related aquatic system responses. These programs are particularly important wherever precipitation monitoring indicates the presence of strong acids and where the probability of possible future contamination is high.

Research Recommendations

I. Conduct a literature search on the effects of H^+ on aquatic organisms.

A literature search on the effects of H^+ on aquatic ecosystems is essential. This search should precede any investigations and should also be done as a continuing endeavor to keep abreast of current research accomplishments.

II. Establish permanent networks for monitoring precipitation chemistry.

To appraise the impact of acid precipitation on aquatic systems, the input to the system must be known. Concentrations of acids, bases, heavy metals, nutrients, organic solvents, and particulate matter should be determined in daily, seasonal, and yearly amounts. A standardized network of precipitation monitoring stations should be established throughout the world. Regional networks should be located in parts of the world where acid precipitation exists and where the potential for future acidification is most likely. Local monitoring near major sources is also required. In addition, several stations should be established in relatively isolated locations to provide reference data.

The following components may be present in precipitation and should be measured at least once a month: H^+, Ca, Mg, K, Na, SO_4, NO_3, Cl, specific conductance, total P, NH_4, alkalinity, titratable acidity, total organic carbon. Other useful measurements might include: Al, Fe, Si, Mn, Zn, Cr, Pb, Cd, Cu, Ni, Hg, PO_4, O_2, total N, color, particulates.

III. Develop criteria and establish permanent networks for monitoring volume discharges, chemistry, and biology of freshwater systems.

Surveillance of lakes and streams is essential for detecting changes in the aquatic life of these water bodies. For areas presently or potentially subjected to acid precipitation, representative lakes and streams (particularly those with low buffering capacity) should be established to monitor the following parameters:

A. Water volume discharge — continuous measurement or measurements sufficient to characterize water flows throughout the year.

B. Water chemistry — measurements in lakes should be made about 5 to 10 times yearly and during periods of limnological change. Streams should be monitored during their critical periods. Measurements should include: H^+, Ca, Mg, Na, K, NO_3, SO_4, Cl, specific conductance, color, temperature, O_2, total organic C, total P, total N, NH_4–N, alkalinity, acidity, Al, Mn, Zn. Measurements of Fe, Si, Cr, Pb, Cd, Cu, Ni, Hg, and PO_4–P might also be useful.

C. Water biology — documentation should include assessments of the following aquatic life:

Lakes—Phytoplankton, zooplankton, zoobenthos, and bacteria/fungi should be monitored four times annually. Macrophytes and fish should be monitored annually.

Streams — Epibenthic algae, invertebrates, fish, and bacteria/fungi should all be monitored annually.

IV. Conduct in-depth studies involving the hydrological, chemical, and biological interrelationships of aquatic systems with respect to small and large accretions of acids, heavy metals, and nutrient ions in acid precipitation.

Studies must determine the nature and extent to which aquatic organisms can tolerate and respond to high concentrations of added substances such as H^+ ions, heavy metals, and other materials that enter the ecosystem in acid precipitation. Examples of the kinds of studies recommended are given below:

A. The effects of acidification and toxicity on cell metabolism, reproduction, and life cycles of aquatic organisms. Among the most important of these are the microflora, phytoplankton, zooplankton, benthos, and nekton.

B. Interactions of acids, metals, and other chemicals with the aquatic system. These should include studies of chronic and acute toxicity, combined reactions, and secondary effects on organisms.

C. The influence of acidification on organism succession.

D. Genetic changes and the extent of short- and long-term species adaption to increases in acidity.

E. Ecosystem mechanisms, natural sources, processes, and limitations in lakes and streams for detoxification and degradation of strong acids, organic acids, heavy metals, and other substances.

F. Effects of acidification on physical aspects of water quality. Such studies should include stream and lake interaction with bottom materials, sediments, suspended particulate matter, translocation of nutrients adsorbed to the suspended particles, changes in light and temperature levels in varied strata of lakes or position in stream locations, content of dissolved oxygen, and conditions favoring fluctuations or stability in oxidation-reduction potentials.

G. Influence of heavy metals and strong acids on aquatic chemistry: solubility constants relative to other ions present in the system; storage and recycling of nutrients in stream and lake sediment.

V. Establish study sites for experimental research on watersheds that involve lakes and streams.

Representative ecosystems, involving lakes and streams and their watersheds, should be set aside for studying the effects of acid precipitation. These systems should range from oligitrophic to near eutrophic bodies of water and from very fragile systems to those well buffered. Research should involve:

A. Integrated approaches for studying whole watersheds. In-depth investigations should be conducted on the interrelationships of nutrient status, acid media, and heavy metals on aquatic life and their distribution and physiological changes, including adaptations to changes in other organisms. Changes in microbial processes, influence of sulfur and nitrogen loadings and transformations, and effects of nutrient cycling within all portions of the ecosystem should be examined as well. Natural undisturbed ecosystems should be compared with artificially manipulated systems as exemplified by the Freshwater Institute, Winnipeg, Canada, in the Experimental Lakes Area (ELA). Effects of short- and long-term nutrient flushing from watersheds to lakes and streams should be included.

B. Experiments to determine possible ways of ameliorating any changes in the chemical and physical characteristics of lakes and streams to some acceptable biological state.

Panel Cochairmen

G. E. Likens
Section of Ecology and Systematics
Cornell University
Ithaca, NY 14853

R. S. Pierce
Forestry Sciences Laboratory
USDA Forest Service
Durham, NH 03824

Panel Members

R. Beamish
Fisheries Research Board of Canada
Nanaimo, British Columbia
CANADA

W. Curtis
Northeastern Forest Experiment Station
Berea, KY 40403

P. Dugan
Department of Microbiology
Ohio State University
Columbus, OH 43210

O. Grahn
Swedish Water and Air Pollution Laboratory
Sten Sturegatan 42
S-402-24 Gothenburg 5
SWEDEN

J. Hornbeck
Northeastern Forest Experiment Station
Durham, NH 03824

H. Hultberg
Swedish Water and Air Pollution Laboratory
Sten Sturegatan 42
S-402-24 Gothenburg 5
SWEDEN

J. Parsons
Botany Department
Southern Illinois University
Carbondale, IL 62901

C. Schofield
Department of Natural Resources
Cornell University
Ithaca, NY 14853

J. Sedell
Coniferous Forest Biome
Department of Fisheries and Wildlife
Oregon State University
Corvallis, OR 97331

R. F. Wright
Norwegian Institute for Water Research
Oslo 3
NORWAY

EFFECTS ON FOREST SOILS

The effects of acid precipitation on soil are best considered together with the vegetation it supports because of the many reciprocal relationships that occur among soil, plant, and aquatic systems. The biotic-soil system constitutes the fundamental interface between the atmosphere and the geologic substratum. In broad terms, this interface serves to transport solar energy via intermediates of photosynthesis and ramifications of the plant root system to the surface of primary minerals in the substratum. Here latent chemical energy of previous eras is activated and added to the total energy supply of the system, and in the process nutrient ions are released to further sustain growth of producer and consumer organisms of all types, particularly those related to the soil.

The effects of acid precipitation will be much greater in some ecosystems than in others. Three primary relationships exist between acid precipitation and the buffering ability of the ecosystem. First, when acid precipitation falls on an ecosystem in which the total capacity of the plants and the soil in which they are growing cannot supply sufficient quantities of basic cations to significantly alter precipitation characteristics, the drainage waters leaving that system will be controlled by the degree of acidity in the precipitation that falls on it. In this case, changes in atmospheric chemistry caused by pollution may be reflected in drainage water chemistry. This ecosystem would experience deterioration of the marginal plant cover, which in turn could lead to further reduction in productive capacity due to soil erosion.

In the second case, when the total buffer capacity of the ecosystem is in approximate balance with the input of acidity from the atmosphere, the productive capacity of the ecosystem will probably sustain itself, and drainage water chemistry will reflect the functioning of the ecosystem rather than the composition of incoming precipitation. However, if further stresses are superimposed on the system, then the buffer capacity may be exceeded, resulting in changes in drainage water characteristics and the ultimate self-sustaining capabilities of the system.

In the third relationship, the buffer capacity of the system far exceeds the acidity added in precipitation. Even if additional disturbances are introduced, recovery would be expected to proceed normally because of the inherent productive capacity of the soil. A more complete understanding of how the natural plant-soil ecosystem functions with and without precipitation pollutants is needed. With respect to soil acidification, are soils acidified by atmospheric pollutants; where does acidification occur; what mechanisms are involved; and what ecosystem components are most affected? Additional research on these and related topics is required to assess the potential impact of acid precipitation on forest soils.

Research Recommendations

I. Establish a network of representative research areas on a global scale to provide baseline data on soil processes both within and external to regions of significant acid precipitation. In addition to such areas, all on-going forest ecosystem research projects are encouraged to include study of acid precipitation.

II. Study effects of acid precipitation on biological processes that affect the soil.

The biotic-soil interface constitutes an extremely complex system, which requires better understanding. A self-acidifying process generally occurs. Organic matter originating in the canopy and dead roots within the soil undergo decomposition in which complex molecules are gradually hydrolized by consumer organisms to constituent compounds and elements. Consumer organisms include microfauna, macrofauna, and microflora. The system is generally saturated with CO_2 and contains organic acids of various types. In addition, microbial oxidation of organic nitrogen to nitrate and organic sulfur to sulfate increases hydrogen ion activity, usually resulting in a lower soil pH. As development of the system progresses, the number of species involved at each trophic level tends to increase, and utilization of all resources becomes more complete. To improve our understanding of this complex system studies should concentrate on:

A. Organic matter decomposition — this should include relationship with and effects on nutrient mineralization and immobilization, particularly with respect to nitrogen, sulfur, and phosphorus; food-web relationships between the soil invertebrate community, soil microorganisms, and bird and animal predators; and the negative and positive selective processes of acid precipitation on decomposer organisms.
B. Nitrogen fixation and volatilization.
C. Soil respiration.
D. Rhizosphere effects and plant root responses.
E. Mycorrhiza.

III. Investigate the effects of mineral weathering and clay development.

The nature and composition of minerals in the substratum are important in determining the rate of clay formation and the type of clay minerals present in the soil. Clay minerals, whether they are of primary or secondary origin, together with organic matter, constitute the colloidal surfaces that regulate behavior and ionic composition of the soil solution, thus influencing soil acidity, nutrient availability to plant roots, and their associated microorganisms and nutrient losses from the soil system, all of which are related to the general buffering capacity of the soil as well as to soil productivity. It is this general buffering capacity that determines the susceptibility of a natural biotic-soil ecosystem to acid precipitation. Research on this should include studies on:

A. Solution equilibria and nutrient loss.
B. Clay mineral formation and alteration of characteristic patterns.
C. Organic matter-clay complexes.
D. Soil physical properties.

IV. Conduct in-depth studies on how acid precipitation affects soil chemical processes.

Since soil chemistry determines to a great extent availability of nutrients as well as possible undesirable elements and compounds to plants, the influence of acid precipitation on soil chemistry should be well understood. Studies are needed in the areas of:

A. pH measurements and soil reactions, particularly oxidation-reduction mechanisms.
B. Hydrogen-ion exchange equilibria with other cations.
C. Micronutrient and heavy metal sorption and release and complex formation.
D. Anion sorption.
E. Direct sorption of atmospheric sulfur dioxide.

V. Examine effects of acid precipitation on nutrient availablity and plant growth.

The effects of soil changes, resulting from acid precipitation, on plants is treated in Section 5 on Effects of Acid Precipitation on Plants. Nevertheless, soils scientists should pursue research on:

A. Species sensitivity to variations in soil acidity and other related changes.
B. Changes in plant succession in different soil systems.

VI. Identify and classify soil systems according to their susceptibility to damage from acid precipitation.

Studies should identify regions that are most likely to be affected and to what extent damage might occur. Research should emphasize:

A. Short- and long-term effects.
B. Damage threshold values.
C. Relationships to other cultural practices and influences, including silvicultural management, species selection, site preparation, fertilization, and fire.

VII. Develop and test ameliorative measures to reduce the impact of acid precipitation on soil systems.

Accommodation procedures such as liming or introduction of new plant species should be investigated along with an examination of any concommitant benefits and injury.

VIII. Develop computer simulation models for:

A. Predicting long-term effects of low-level inputs of acidity on soil characteristics and ecosystem productivity.
B. Predicting long-term effects of ameliorative measures.
C. Identifying sensitive soil factors and processes.
D. Establishing priorities for critical research needs.

Panel Cochairmen

L. O. Safford
Northeastern Forest Experiment Station
USDA Forest Service
Durham, NH 03824

G. K. Voigt
Yale University
New Haven, CT 06510

Panel Members

D. L. Dindal
New York State College of
Environmental Science & Forestry
Syracuse University
Syracuse, NY 13210

A. L. Leaf
New York State College of
Environmental Science & Forestry
Syracuse, NY 13210

J. O. Reuss
National Ecological Research Laboratory
National Environmental Research Center
U.S. Environmental Protection Agency
Corvallis, OR 97330

C. O. Tamm
Department of Plant Ecology
and Forest Soils
The Royal College of Forestry
Stockholm, SWEDEN

J. P. Vimmerstedt
Department of Forestry
Ohio Agricultural Research and
Development Center
Wooster, OH

G. F. Weetman
University of New Brunswick
Frederickton, NEW BRUNSWICK

C. G. Wells
Southeastern Forest Experiment Station
USDA Forest Service
Research Triangle Park
Raleigh, NC

L. H. Wullstein
Department of Biology
The University of Utah
Salt Lake City, UT 84112

EFFECTS ON FOREST VEGETATION

Vegetation covers most of the land surface-area of the earth. Thus, the surfaces of leaves and stems are the initial deposition sites for airborne matter of all kinds. In a mature forest, an average raindrop will be intercepted by three tiers of foliage before it reaches the soil.

Acidic precipitation, therefore, can affect vegetation both through direct contact with external plant surfaces and through root interactions in the soil.

Acidic and other substances in the atmosphere cause a variety of demonstrated effects on vegetation. A most striking example has been the submarine encroachment of peat moss (Sphagnum spp.) into lakes and streams subjected to acidic precipitation in Sweden. Analyses of forest growth in southern Sweden from 1896 to 1965 show a 2 to 7 percent (average 4 percent) decrease in growth between 1950 and 1965; scientists have attributed this to acidification. Several attempts to quantify similar responses from acidification on forests in the United States have been inconclusive.

Among many reported direct effects of natural and simulated acidified rain on vegetation are: alterations in cuticular features such as stomata size and frequency, which are related to acidity; increased bark acidity; changes in the physiology of foliar organs; alteration in root functions; direct injury to the foliage of conifer and deciduous trees; poorer germination of seeds; accelerated leaching of nutrients from foliage; increased leaching of plant nutrients from humus; inhibition or stimulation of plant diseases; and inhibition of nitrogen-fixing bacteria in herbaceous crops.

Much greater knowledge of the injurious and beneficial effects of acid precipitation and other atmospheric substances on vegetation is essential. Research is required on a broad front and should include effects on forest growth, regeneration, reproduction, and related factors needed to maintain ecological stability.

Research Recommendations

Initial emphasis in research should be aimed at identification of specific organs, species or types of plants, physiological processes, or biological interactions that are influenced by acidic precipitation. These tests should be made with individual plants or simple symbiotic relationships and simple soil systems. These initial efforts should focus on processes that are most likely to be affected by acidic precipitation such as: erosion of cuticular waxes, activity of bacterial symbionts, or growth of plants in soils with low buffering or base exchange capacity.

Concurrently, monitoring networks should be established to measure changes in the chemistry of precipitation on a continuous and long-term basis. Surveys should be conducted to identify regions and types of vegetation that are most likely to be affected by acidic precipitation. As the monitoring networks bcome functional, attempts should be made to correlate effects observed in the surveys with rainfall parameters. This effort should be integrated with other forest, agricultural, hydrological, and geological surveys. Specific research needs follow:

I. Establish permanent networks to monitor the chemistry of air and precipitation throughout the world.

Monitoring networks are required to quantify potentially injurious substances and beneficial nutrient elements deposited from the atmosphere into agricultural, forested, and aquatic sites. These networks should be designed with the following criteria:

A. Standardized collection and analytical methods.
B. Long-term monitoring in both rural and urban regions.
C. Analyses of air, dry deposition and precipitation samples to include: NO_2, NO_3, PO_4, total P, K, Ca, Mg, SO_3, SO_4, Mn, Zn, Cu, Fe, Mo, SiO_4, Al, Na, Cl, Pb, Ni, pH, total acidity, free acidity, and organic acids.

D. Integration with established studies such as those developed in the International Biological Program, the Man in the Biosphere Program, and research watersheds maintained and operated throughout the world.

II. Perform controlled experiments with simulated rain.

Controlled experiments are needed to measure responses of vegetation to natural and simulated rains in order to identify and determine the impact of acidity. Care should be taken to note chemical and physical properties of these rains. Experiments in growth chambers, controlled environmental facilities, and greenhouses on individual plant and simple soil systems can simulate elementary ecosystems. Field chambers with communities of plants can simulate more complex ecosystems. Plant effects of particular importance may be:

A. Injury—measured by suitable percentage scales.
B. Growth—measured as leaf area, plant height, yield, total biomass.
C. Reproduction—both direct effects on reproductive systems and possible genetic effects.
D. Physiology—photosynthesis, respiration, nutrient uptake.
E. Biochemistry—pool changes, enzymes affected, energy relations.
F. Interactions and predisposition—air pollutants, pathogens, insects, other environmental stress factors.
G. Other effects—changes in associated flora (lichens, mosses, phyllosphere, and rhizosphere organisms), erosion of cuticular leaf surfaces, development of plant organs, animal browsing preferences.

III. Investigate ecological processes.

Effects of precipitation on vegetation must account for influences of supporting soils and water. Therefore studies of these ecological processes are necessary to determine the impact of acidity on plants in their total environment.

A. Nutrient cycling—including leaching of nutrients from plants and soil.
B. Base-exchange capacity of soils — displacement of cations by hydronium ions.
C. Nitrogen fixation—by blue-green algae, symbiotic and free living bacteria, simple ecosystems.
D. Nutrient uptake—effects on anion and cation uptake by roots.
E. Rhizosphere relationships — effects on microflora and microfauna of the rhizosphere.
F. Formation and function of mycorrhizae.
G. Species and genetic diversity in natural forests and grasslands.
H. Soil-plant-animal interrelationships — study both simple and complex associations.
I. Ecosystem stability — changes in the density and diversity of plant and animal species over time.

IV. Develop computer models for predicting ecosystem changes.

If significant alterations in vegetation are detected, computer modeling could provide important information on potential long-term effects that might occur. Such studies might also improve our understanding of how a complex forest ecosystem works. Furthermore, these models might be useful for testing such proposed remedial actions as:

- Liming of soil to neutralize excess acidity and determine costs and benefits.
- Development of acid-tolerant varieties of economic plants.
- Development and enforcement of air-quality standards for emission and/or ambient concentrations of acidifying substances.

Panel Cochairmen

W. W. Heck
Department of Botany
North Carolina State University
Raleigh, NC 27607

E. B. Cowling
Department of Plant Pathology
North Carolina State University
Raleigh, NC 27607

Panel Members

L. S. Dochinger
USDA Forest Service
Northeastern Forest Experiment Station
Delaware, OH 43015

H. Holtberg
Swedish Water and Air Pollution
Research Laboratory
Sten Sturegaten 42
Goteborg, SWEDEN

J. Jacobson
Boyce Thompson Institute for
Plant Research, Inc.
Yonkers, NY 10701

H. C. Jones
Tennessee Valley Authority
Environmental Biology Branch
Muscle Shoals, AL 35660

W. Knabe
Landesanstalt fur Immissions und
Bodennutzungschutz des Landes
Nordrhein-Westfalen
32 Essen, Wallneyer Strasse 7
GERMANY

R. G. Krebill
Forest Disease Research
USDA Forest Service
Washington, DC 20250

S. Krupa
Department of Plant Pathology
University of Minnesota
Minneapolis, MN 55108

J. Lee
National Ecological Research Laboratory
Environmental Protection Agency
Corvallis, OR 97330

S. N. Linzon
Air Resources Branch
Ministry of the Environment
Toronto, Ontario,
CANADA

D. S. Odén
Department of Soil Science
Agricultural College
Ultuna, SWEDEN

E. W. Ross
USDA Forest Service
Northeastern Forest Experiment Station
Delaware, OH 43015

D. S. Shriner
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN 37830

K. Stefan
Forstliche Bundesversuchs—
Anstalt Wien
4 1131 — Wien/Vienna
AUSTRIA

C. O. Tamm
Department of Plant Ecology and
Forest Soils
The Royal College of Forestry
Stockholm, SWEDEN

F. A. Wood
Department of Plant Pathology
University of Minnesota
Minneapolis, MN 55108

ENERGY-RELATED ISSUES

The world is presently facing serious problems deciding environmental tradeoffs for the sake of energy production at the least immediate economic cost. The relationship between acid precipitation and energy-related issues has been discussed previously in Section 1. Furthermore, many other major issues in the world may affect or be affected by acid precipitation; e.g., health, fuels policy, air quality and standards, shortages of natural resources, critical energy needs, international affairs, environmental tradeoffs, land-use policy, water quality, and transportation may all be related in one way or another. It is clear that the acid precipitation-energy relationship raises many questions that need to be answered.

Research Recommendations

Since acid precipitation may produce serious consequences in the forest ecosystem and possibly elsewhere, methods for decreasing this acidity must be found. Advances are necessary in many areas, including:

I. Reduce acid-forming emissions from combustion of present fuels.

Numerous programs are under way to develop economic methods for removing sulfur oxides and related atmospheric pollutants from emissions. These efforts should continue to be pursued vigorously. In addition, programs aimed at removing sulfur from fuels prior to combustion should be expanded. Economic incentives are needed to increase these efforts and to develop use for waste materials that result from fuel cleansing and stack emissions.

II. Develop alternate sources of energy.

A. Alternative energy sources for fossil fuels that do not introduce acidifying substances into the atmosphere and do not pose equal or greater environmental hazards are greatly needed. The environmental impact of non-acidifying energy sources such as solar, wind, nuclear, hydrological, and ocean currents and waves and thermal gradients require careful analysis and comparison with the impact of fossil fuels. When environmental impact assessments are made for other possible sources of energy such as geothermal and ocean tides, an examination should be made of their possible contributions to acidic precipitation.

B. Research and economic analyses on vegetation utilization as fuels should be accelerated. Vegetation is also a significant energy resource that is produced through biological processes that utilize solar energy. Plants provide us with supplementary heat energy and may ultimately be an important source of liquid and gaseous fuels.

III. Clarify the relationship between sources of acidic pollutants and forest sinks.

Forests are a major sink for atmospheric pollutants. Their role in cleansing the atmosphere should be thoroughly investigated for both wet and dry removal and for possible utilization of atmospheric trace substances as beneficial nutrients. An understanding of these potentially ameliorative processes along with injurious responses is required for establishing air-quality standards for major sources of acid precipitation.

IV. Identify primary sources of acidic pollutants in the atmosphere throughout the world.

In order to determine regions where acid precipitation may be a potential problem, an inventory of major natural and anthropogenic sources of acidifying substances in the atmosphere is required. This inventory should be combined with model studies of atmospheric transformations and transport and with an evaluation of susceptibility of various ecosystems to increasing acidity. Results of such studies may be important for establishing future land-use practices.

V. Perform studies relating to optimum utilization of energy resources, including acid precipitation as a major environmental threat.

Panel Cochairmen

E. Walther, Manager
Food Production Climate Mission
Charles F. Kettering Foundation
Dayton, OH 45429

T. A. Seliga
Atmospheric Sciences Program
The Ohio State University
Columbus, OH 43210

Panel Members

S. Baruch
Environmental Projects Manager
Edison Electric Institute
New York, NY 10016

R. Beadle
Physical and Chemical Transport Program
Environmental Programs
Division of Biomedical and Environmental Research
U. S. Energy Research & Development Administration
Washington, DC 20545

H. M. Benedict
Stanford Research Institute & Kennecott
South Pasadena, CA 91030

C. Brosset, Professor
Swedish Water and Air Pollution Research Laboratory
Sten Sturegation 42
S-402 24
Gothenburg 5, SWEDEN

P. Coffey
Senior Research Scientist
Air Resources Division
New York State Department of Environmental Conservation
Albany, NY 12222

D. W. Cole
Coniferous Forest Biome
Ecosystem Analysis Studies
U. S. International Biological Program
University of Washington
Seattle, WA 98195

L. S. Dochinger
USDA Forest Service
Delaware, Ohio 43015

W. Knabe
Landensanstalt fur Immissions und Bodennutzungsschutz des Landes NW
43-Essen Bredeney
Wallneyer Strasse 6
WEST GERMANY

B. Ottar, Director
Norwegian Institute for Air Research
P.O. Box 115
N-2007, Kjeller, NORWAY

N. Overrein
Norwegian Forest Research Institute
1432 As-NLH
NORWAY

P. W. Summers
Chief, Atmospheric Dispersion Division
Air Quality and Inter-Environmental Research Branch
Environment Canada
Downsview, Ontario, CANADA M3H 5T4

H. Tarkow
Acting Assistant Director
Fiber and Chemistry Research
USDA Forest Service
Forest Products Laboratory
Madison, WI 53705

F. Wright
Norwegian Institute for Water Research
Blindorn
Oslo 3, NORWAY