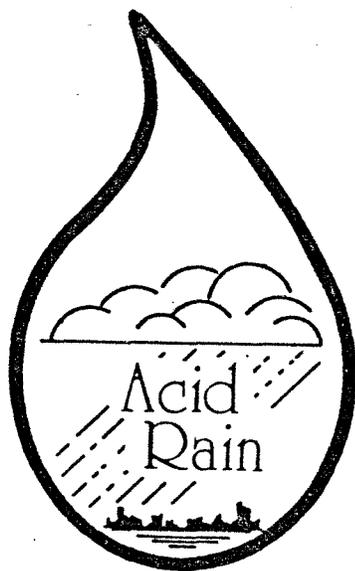


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ACID RAIN - AN OVERVIEW

INTRODUCTION

Although the phenomenon of "acid rain" (more correctly termed acid deposition) was identified in the city of Manchester, England, by Angus Smith as long ago as 1852¹, and described more thoroughly in 1872², modern scientific research has been going on only since the mid-1950's^{3,4}. Public concern about the problem began in Europe in the late 1960's⁵, and arose in North America ten years ago⁶. My purpose here is to present an overview of the nature of acid deposition from the atmosphere, its sources, history, and present status as a serious environmental problem. I shall also offer my own view of present research needs, and of what can and should be done about the problem.

THE NATURE OF ACID DEPOSITION

Acid precipitation is a mixture of strong mineral acids -- sulfuric, nitric, and in some locations hydrochloric⁷ -- in rain and snow. (Unfortunately, because of the diversity of cations in precipitation, a stoichiometric assignment of hydrogen ions to non-marine sulfate, nitrate and chloride is not justified^{7,8}, although it is a common practice in calculating the contribution of sulfur and nitrogen oxides to precipitation acidity.) We must also recognize that acids are deposited from the air at times when rain and snow are not falling, by processes of so-called dry deposition. Such deposition is seldom measured, and requires much more study^{9,10}. There may also be weak organic acids and carbonic acid present in

rain, but they are seldom important sources of free hydrogen ions¹¹ where the pH is well below 5. Several toxic heavy metals, including lead, cadmium and mercury, often accompany acid rain¹⁰, which may also leach such metals from soils or sediments along with toxic aluminum^{12,13}. A variety of organic micropollutants is found in acid rain, including alkanes, phthalic acid esters, fatty acid ethylesters, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons -- some of which are carcinogens^{10,14}. Some plant nutrients, for example nitrogen, sulfur, potassium and calcium, are also deposited in acid rain, but because they are accompanied by a diverse array of toxins, they are better supplied directly as fertilizer by farmers. Acid rain is an extremely inefficient method of crop fertilization!

THE SOURCES OF ACID DEPOSITION

There are several sources of acid rain, some natural and others anthropogenic.

Natural Sources

In 1939, Bottini¹⁵ recorded acid rain dominated by hydrochloric acid around the volcano Vesuvius. Forty years later, Hutchinson et al.¹⁶ reported acid deposition on the Smoking Hills in arctic Canada, where natural fires in exposed beds of lignite generate large amounts of sulfur oxides that are converted to sulfuric acid. Thus, even remote areas can be subject to acid rain, and recent studies by the Global Precipitation Chemistry Project have documented other cases where weak and strong acids are deposited from natural and anthropogenic sources (J.N. Galloway, personal communication).

Coastal mudflats and salt marshes are possible sources of natural acid deposition, generating volatile sulfur compounds that may become oxidized in the atmosphere to sulfuric acid¹⁷. It appears that ammonia is also generated from local sources and neutralizes part of the sulfuric acid. Convincing evidence is lacking for major acid

emissions from such coastal sources, but the possibility needs a good deal more investigation. An argument against their importance can be drawn from the absence of strong acidity in rain at coastal stations in the U.S.A.¹⁸. We can see a striking decline of chloride in rain away from the U.S. coast as the influence of sea spray declines^{19,20}, but we do not see similar declines of hydrogen and sulfate ions.

Anthropogenic Sources

The major sources of acid deposition are anthropogenic. The combustion of fossil fuels (chiefly coal and oil) and the smelting of sulfide minerals generate the gaseous precursors of acid rain, sulfur and nitrogen oxides that can contaminate not only local but also far distant regions²¹. During long-range transport the acids may be wholly or partly neutralized, for instance by alkaline fly-ash²², cement dust²³, blown soil particles⁸, or ammonia produced in agricultural areas²⁴. Combustion of fossil fuels appears to generate comparatively small amounts of ammonia^{25,26}, though urban concentrations tend to exceed those of rural areas²⁷.

Case Studies

To establish the origin of acid rain most convincingly it is best to work relatively close to a source, because the situation there is less likely to be complicated by extraneous processes of mixing from other sources or neutralization by alkaline materials than it is farther away. For example, the hydrochloric acid in rain close to Vesuvius, which brings rain pH down as low as 2.8, must be volcanic in origin -- the more so because sulfate is very low in relation to chloride. Ponds near the Smoking Hills in arctic Canada, with pH values down to 1.8 and very high sulfate concentrations, must owe their acidity to the sulfuric acid generated there by burning lignite.

Similarly, Angus Smith¹ and Crowther and Ruston²⁸ found acidity to decrease sharply going away from the cities of Manchester and Leeds in England.

An equally convincing case for acid deposition of anthropogenic origin can be made for the area northeast of the iron-sintering plant at Wawa on the northeast shore of Lake Superior²⁹. The pH values of lakes in that region, which are normally between 6 and 7, decline to values as low as 3.2 close to the sintering plant while sulfates rise tenfold. There are some naturally acid bog lakes in the Wawa region, but they can be distinguished readily from the lakes acidified by man by their brown tea-color. For the acidity of clearwater lakes close to the sintering plant, there is no credible source other than acid deposition, caused by the sulfur dioxide emitted from that plant.

Even at considerable distances, it may still be possible to ascribe rain acids clearly to their anthropogenic sources. For instance, in the English Lake District, the rain is acid and rich in sulfates when the wind blows from the south and east, in the direction of the major industrial districts of northern Britain. Those rains are also black and sooty. In contrast, when the wind blows from the west -- from the Irish Sea -- the rains are clear, lower in acidity, and rich in sea salt^{30, 31}. On a broader scale in Britain, bog pools with surface waters fed wholly by atmospheric precipitation become increasingly acid as one travels from remote areas toward the major industrial centers of northern England. In the remote bog pools pH values are usually around 4.5, whereas closer to the industrial areas the pH declines to 3.9, and even to 3.2 immediately outside the industrial city of Sheffield³².

In the United States the area of heaviest sulfate deposition²⁰ and acid precipitation¹⁸ is in and downwind of the chief coal-using states of Ohio, Indiana and Illinois, which produce about one-quarter of total U.S. emissions of sulfur oxides and one-sixth of nitrogen oxide emissions. Deposition of heavy metals is focused upon the same area³³. The only credible reason for this area being the center of acid precipitation in the United States is the abundance of closely packed, urban/industrial emission sources in these and nearby states,

where anthropogenic emissions strongly dominate those from natural sources³⁴. Unfortunately, the large number of anthropogenic sources creates a pool of acid air pollution over the whole northeastern part of the continent that makes it impossible to trace damage to an individual site from an individual source, and hence to establish an explicit causal connection.

Satellite photos show that pollution can travel long distances, even into the midwest with certain weather patterns³⁵, and sulfur dioxide is converted to sulfuric acid along the way. The rate of conversion is extremely variable both temporally and spatially, perhaps dependent upon the abundance of some rate-limiting oxidant³⁶. Nevertheless, it is not so variable as to obscure the fact that both in Europe and North America the areas of acid precipitation are closely linked to centers of urban/industrial activity.

Complex Situations

Not all situations are as clear as those examined above. For example, in Nova Scotia there is a gradient of precipitation pH from 4.6 in the southwest -- near to urban/industrial sources of sulfur and nitrogen oxides in New England -- to 5.3 in the more remote northeastern parts of the province³⁷. However, hydrogen ion is not closely related either to sulfate or to nitrate ion in these rains, presumably because of interactions among diverse emitting sources and equally diverse sources of neutralization.

One complicating factor in situations like this is the mix of different acids involved. On the west coast of the United States, where vehicle emissions predominate, it appears that nitric acid is the chief acidifying agent in rain^{38, 39}. In northern English cities, where coal high in chlorine is burned, hydrochloric acid appears to be the dominant acid, even though sulfate exceeds chloride in the rain⁷. Neutralizing agents are also of great significance. In the southeastern United States, hydrogen ions correlate with sulfate minus

calcium ions, and bicarbonate ions correlate with calcium minus sulfate ions, because some of the rain acids are neutralized by blown soil dust⁴⁰.

In Minnesota we find a mixture of different acids and different neutralizing agents as we pass across the northern part of the state from North Dakota. In the year 1978-79, precipitation pH ranged from 5.3 in agricultural southeastern North Dakota to 5.0 in forested northwestern Minnesota and 4.7 in forested northeastern Minnesota. Hydrogen ion was not clearly related either to sulfate or to nitrate, and the confounding factors appear to have been windblown calcareous soil and gaseous ammonia from the cultivated prairie⁴¹. In this connection, following severe blizzards, snows from the Dakotas may be so contaminated with soil as to have a pH of 8 when melted⁸. It is also important to remember that although ammonia may neutralize sulfuric acid in the atmosphere, producing ammonium sulfate, the product is an acidifying agent in sensitive soils⁴². Farmers have known for a long time that if they fertilize with ammonia sulfate, their soils will require liming.

HISTORY OF THE PROBLEM

The phenomenon of acid deposition may have occurred in some cities as far back as the 17th century. Sulfur pollution became serious then in London^{43, 44}. Moreover, we know that deposits of sulfate in the Greenland icecap have increased coincident with the beginning of the industrial age in Europe⁴⁵. The spread of acid rain over broad rural regions, and internationally through transboundary pollution, has probably developed chiefly in this century, and especially since World War II. In the last several decades, combustion of fossil fuels has risen greatly in western Europe and the northeastern United States, especially in power plants. Tall smoke stacks have also been employed to meet air quality standards, and this has allowed pollutants to spread more widely from their sources. At the same time, stack-scrubbing devices have come into use, removing potentially neutralizing fly-ash from the emissions.

A problem of great current interest is whether acid deposition is increasing and spreading. There is some evidence, both from Europe and from eastern North America, suggesting that this is so¹⁸. The evidence is not without flaws^{36, 46, 47}, though some of the criticisms have been disputed⁴⁸. Methods have changed, sites have been shifted, and we do not have enough satisfactory trend data to resolve this problem conclusively. Nevertheless, even if acid rain is not getting worse -- and we are not sure at present whether this is so -- it is a clear and present danger to certain types of ecosystem. Of that we can have no doubt whatever!

Early Investigations

Before passing to another topic, I would like to recount briefly the history of studies on acid precipitation^{3, 4}. In cities (but not in the surrounding countryside) it was first described by Angus Smith in 1852¹, working in and around the city of Manchester in northern England. In 1872, Smith extended his studies to cover the United Kingdom, and published his classic book Air and Rain². Then in 1911 and 1912, Crowther and Ruston²⁸ and Cohen and Ruston⁴⁹, working in and around the city of Leeds in northern England, duplicated much of Smith's early work and carried out experiments on the effects of acid rain, both upon vascular plants and upon microbes involved in the cycle of nitrogen. The acidification of rain in many British cities was later demonstrated by Parker⁵⁰. Acid rain in rural areas was probably first demonstrated by Bottini¹⁵ near the volcano Vesuvius. Between 1939 and 1954, there were scattered pH measurements of rain in a variety of areas³, but the data were not subjected to detailed analysis.

Modern Studies

A new era in studies of acid deposition began in 1955, when it was discovered to be widespread in rural areas far from urban, anthropogenic sources. In that year, Barrett and

Drodin²³ discovered acid rain in Scandinavia, Houghton⁵¹ found fog and cloud water in New England to be acid, and I³⁰ observed acid rain in the English Lake District whenever the wind blew from urban/industrial areas. After further work on acid rain and its ecological consequences,³¹ I returned to Canada and worked on the acidification of lakes by sulfur oxides from the metal-processing plants at Sudbury⁵² and Wawa²⁹. Recognition that the ecological damage done by acid deposition could be a major international problem came in 1968 with the work of Svante Oden in Sweden⁵. Similar problems were recognized in the United States by Likens and his associates in 1972⁶.

ENVIRONMENTAL CONCERNS

Acid deposition can bring about a great variety of geochemical and ecological changes in the biosphere.

Lake Acidification

The primary reason for concern is that acid deposition acidifies streams and lakes on coarse, sandy soils low in lime. The effect is seen particularly in headwater areas and in wet montane environments, wherever sulfate loading from anthropogenic sources is strong. (Nitric acid, the other major component of acid deposition, is likely to be less significant because it is consumed more effectively by biological processes⁵³). In northern England, several lakes on soils poor in lime were very acid by the 1950's^{54, 55}. In southern Scandinavia, thousands of lakes and streams have been acidified over the past few decades¹⁸. Hundreds of lakes and streams in the Adirondacks, Maine, Ontario, and Nova Scotia have likewise shown acid stress in recent years, and thousands more are threatened, particularly in Canada. Acidification may be exceptionally severe as the accumulated snowpack melts in spring⁵⁶, and this may be the first sign⁵ of the phenomenon in lakes and

streams that otherwise appear normal. (In such a case, nitric acid flowing over frozen ground can be an important contributor^{53, 56}.)

All of these lakes are either near to or downwind from major anthropogenic sources of sulfur and nitrogen oxides. Clearwater lakes on similar substrata upwind of such sources, or far distant from them, have not become acidified in the same way; for example, in northern Norway and Sweden, Finland, Newfoundland, northeastern Minnesota, and the Experimental Lakes Area of northwestern Ontario. These areas are, however, at risk if acid rain continues, and especially if it worsens and spreads.

It should be emphasized that neighboring lakes in the sensitive regions exposed to acid deposition may become acidified at quite different rates. For example, three lakes close together in the Adirondacks have exhibited very different responses that depend upon different characteristics of their watersheds, as shown in excellent research sponsored by the Electric Power Research Institute⁵⁷. A great variety of factors is involved in determining the vulnerability of individual ecosystems to acid deposition: anthropogenic, geologic, climatic, topographic, biotic and episodic (see Table 8.1 in National Research Council²¹).

Consequences of Lake Acidification

The chemical and physical consequences of lake acidification include increased leaching of calcium from terrestrial soils²⁹, mobilization of heavy metals, such as aluminum, zinc and manganese¹², and an increase in the transparency of lake waters⁵⁸. The biological consequences include marked changes in communities of aquatic plants and animals, with a progressive lessening of their diversity (see papers and references in the synopsis of aquatic biota, Drabløs and Tollan⁵⁹). In a few extreme cases a lessening of primary productivity is observed, but in many cases there is merely a change toward lesser pelagic and greater benthic production. Whether or not primary plant production decreases,

there is a progressive elimination of sensitive species of plants and animals, including fish -- which are completely exterminated under severe acidification. The European roach, and the American smallmouth bass and walleye, are extremely sensitive. Perch are relatively resistant. Aluminum leached by acid rain from sensitive soils is strongly implicated in the effects on fish, chiefly through damage to gill epithelium⁶⁰. Other effects include inhibition of spawning and hatching, embryonic malformation, upset of salt balance in the blood, and growth retardation (see papers and references in the synopses of aquatic biota, Drablos and Tollan⁵⁹). Where there is a sudden stress after snow melt, fish kills can result.

It should be pointed out again here that naturally acid lakes are also known. Some are volcanic^{61, 62}, others owe their acidity to oxidation of pyrites⁶³, but most are the result of drainage from adjacent, strongly acid peat bogs. Such bog lakes are tea-colored owing to organic matter dissolved from the peaty drainage basin, and can be further acidified by acid rain, as shown by experience at Wawa²⁹. Their ecology and biogeochemistry deserve further study.

The Threat of Further Problems

Many ecologists believe that over the longer term -- several decades to a few centuries -- acid deposition may further impoverish forest soils developed on sandy substrata poor in lime. As a consequence of accelerated leaching of nutrients, such as phosphorus, potassium, magnesium and calcium from these soils, forest productivity could eventually be reduced. There is as yet no conclusive evidence for such a phenomenon. Indeed, nitrate in acid rain may actually benefit forest growth initially, because nitrogen is often the major limiting nutrient for trees on poor soil⁶⁴. However, the deleterious effects of increased nutrient leaching may counter such a benefit, at least over the long term. Low pH may also inhibit nitrogen recycling in forest soils, perhaps vitiating the long-term benefit of nitrogen added as nitrate in acid rain⁶⁵.

In this context, we must remember that poor soils have been known for a long time to be undergoing a slow process of natural leaching and acidification that is steadily reducing their store of essential plant nutrients and altering their biota^{66, 67, 68}. Acid rain may hasten appreciably this natural process of soil impoverishment⁶⁹. Moreover, recent studies of forest ecology in Germany, New England and elsewhere^{70, 71}, suggest the possibility of serious forestry problems associated with the liberation of soluble aluminum by acid deposition and consequent damage to the fine tree roots in the mineral soil. Recent studies in the New Jersey pine barrens⁷² have linked a decrease in the growth rates of three species of pine to local stream acidification; other factors, such as drought, fire, pests and atmospheric oxidants, do not seem to be responsible. Further detailed study of these problems is obviously of great importance.

Some have suggested that it is not acid deposition but changes in forestry practices and other aspects of land use that have caused the acidification of lakes in recent decades. However, the phenomenon has been observed above treeline in Scandinavia, and in other places where forests have remained unchanged. Although land-use changes in Norway may influence acidification, they appear not to have been the major factor⁶⁹.

Other Effects

We should remember that acid precipitation has other effects than the ecological ones that have been discussed so far. It (along with precursor gases and acid sulfate particles) causes severe surface damage to metals, and corrodes limestone structures, monuments, etc.⁷³. It can also mobilize heavy metals from pipes into supplies of potable water³³. Some ground waters are known to have become acidified in Sweden⁷⁴. Moreover, the acid sulfate particles that contribute to acid precipitation are in the size-range that penetrates deep into the lung, and they may well exacerbate lung disease and increase mortality rates^{33, 75}. Present epidemiological, toxicological and clinical studies of the effects of sulfur dioxide

and acid sulfate particles are not adequate to demonstrate conclusively that there are ill effects at ambient levels, but the problem certainly requires further attention and merits our concern⁷⁶. There is also some potential for crop damage during exceptionally severe episodes of acid deposition⁷⁷, although this does not seem likely to become a serious and widespread problem.

RESEARCH NEEDS

There are, of course, still many things that we need to learn about the nature of acid precipitation, its origin, chemistry, transport, deposition, and ecological effects. Heavy metals and organic micropollutants should be included in standard analyses, and their synergistic effects with the acid in precipitation should be examined. We require better data on dry deposition, an area of great uncertainty in loading calculations. In particular, we must develop better sensitivity indices⁷⁸, as well as more and better dose/response data⁷⁹ for lake ecosystems -- that is, how much damage (chemical or biological) is produced by a given degree of acid loading. Models of the kind developed for cultural eutrophication of lakes⁸⁰ should be equally feasible for lake acidification. We also need data on rates of recovery after lake acidification has been stopped. The potential problem concerning forest productivity, about which there are so many uncertainties, could become extremely serious in the relatively near future. A major, long-term research program on this subject is imperative.

We cannot expect quick answers and easy solutions for our environmental problems. Scandinavian experience⁶⁹ suggests that we must plan monitoring programs and experimental studies to last for decades; the forest program may require study over at least one or two rotations of several decades each. More emphasis should be given to whole-watershed studies of the biota and its physico-chemical environment, examining the transfer of

materials from the atmosphere to upland and eventually to wetland and aquatic ecosystems, and looking at effects along the way.

A CALL FOR ACTION

Although there are gaps in our understanding of acid deposition and its effects, and questions may be raised concerning some of the evidence^{36, 46, 47, 81, 82, 83}, the weight of all the evidence taken together clearly indicates that acid deposition is a very serious and widespread environmental problem, caused largely by anthropogenic emissions of the oxides of sulfur and nitrogen during the process of burning fossil fuels. According to President Carter⁸⁴, acid rain is "one of the two most serious global environmental problems associated with fossil fuel combustion", and it is regarded by the Canadian Government as Canada's most critical environmental problem⁸⁵. Only a very few of the many scientists working actively on the problem (i.e., publishing in referenced journals and participating in the major symposia from Columbus, Ohio, in 1976 to Sandefjord, Norway, in 1980) have questioned such a viewpoint, which is strongly reinforced by recent reports of the national Research Council's Committee on the Atmosphere and Biosphere²¹ and the Subcommittee on Acid Rain of the Standing Committee on Fisheries and Forestry of the Canadian House of Commons⁸⁶.

In my opinion -- speaking now as a concerned citizen rather than as a scientist -- the evidence is sufficiently compelling to justify a major attempt to reduce the gaseous precursors of acid rain, because ameliorative measures, such as liming^{87, 88} cannot be applied over more than a small fraction of the sensitive areas undergoing -- or liable to undergo -- serious acidification. This is also the opinion of the Canadian Government, as expressed by its Minister of Environment, John Roberts⁸⁹, and of the National Commission on Air Quality⁹⁰. Many possible options are available for emission reduction: coal washing, stack scrubbers, novel combustion technologies, low-sulfur fuels, and alternative energy

sources such as sun, wind, water (including geothermal and ocean-thermal sources), and **biomass**. Last -- but by no means least -- conservation is the most environmentally sound **option**, which can be cost-effective in many cases⁹⁰ and need not compromise human **welfare** if we focus upon the energy we now waste casually in the pursuit of planned **obsolescence** and conspicuous consumption.

A Suggested Goal for Emission Reductions

The degree of emission reduction is, of course, open to debate. Although we have a **reasonable** idea of the level of precipitation acidity that will allow the preservation of **threatened** ecosystems, we cannot yet predict the likely reduction in precipitation acidity at **specific** locations for any given reductions in local emissions of sulfur and nitrogen oxides from various sources⁹⁰. On the first point, the National Research Council's Committee on the Atmosphere and Biosphere²¹ has suggested that the average acidity of precipitation should not exceed that represented by a pH of 4.6 to 4.7, the level below which acidification of sensitive lakes is detectable at present (cf. Evans et al.⁹¹). This would mean a reduction in the atmospheric deposition of hydrogen ions by 50% or more in those areas of the United States most affected by acid precipitation²¹. The question then becomes: what reduction of emissions would bring about such a reduction in the deposition of hydrogen ions? We know that the response of precipitation pH to atmospheric loadings of interacting sulfur dioxide, nitrogen oxides, oxidants, and metal catalysts is complex and almost certainly non-linear. However, it may be useful to approach the problem by considering that all emissions of sulfur dioxide and nitrogen oxides will eventually be oxidized to the acid form somewhere or other. A good deal of the nitrate will, however, be consumed by the biota. Therefore, the relationship of lake pH to atmospheric loading of non-marine sulfate may provide us with guidance as to what is acceptable (cf. Almer et al.)⁷⁹. Annual sulfate loading in bulk precipitation is about 7-14 kg ha⁻¹ in northwestern Ontario⁹² and 10-18 kg ha⁻¹ in northern

Minnesota^{92, 93}; acidification of sensitive clearwater lakes has not yet been detected in either location. Loadings exceed these ranges in areas of North America where lake acidification has been observed, for example in Nova Scotia where pollution is not yet severe (25 kg ha^{-1})⁹⁴, and in the heavily polluted Adirondack Mountains (43 kg ha^{-1})⁹⁵. This last figure lends strong support to the words of John Roberts, Minister of the Environment in Canada⁹⁶: "We must reduce drastically the amount of acid-causing pollution that is being emitted..." With this in mind, staged empirical cutbacks -- with the goal of reducing atmospheric sulfate loadings to sensitive areas eventually below $15\text{-}20 \text{ kg ha}^{-1} \text{ yr}^{-1}$ -- might be the most appropriate way to approach a solution to the problem of acid deposition. If we resort to conservation, or energy sources other than fossil fuels, then emissions of nitrogen oxides will also be reduced.

New techniques of elemental signatures^{97, 98} may be useful in pinpointing the sources of deposition to a particular region that ought to be cut back, although their applicability to the northeastern U.S. is as yet uncertain and is being argued by K.A. Rahn and D.G. Hawkins in widely circulated but unpublished manuscripts.

Action Now or Later

As to the argument that we should not act until the evidence is much stronger, there has long been ample precedent for action on environmental problems even though the chain of causation is far from complete. An early, dramatic instance came in 1854 during a great cholera epidemic in London, when Dr. John Snow confirmed his hypothesis that cholera was water-borne by having the handle removed from the Broad Street pump in Soho⁹⁹. This experiment was made before the germ theory of disease was proven, and the cholera bacterium was not isolated until 1884. Thus, the chain of causation was not at all complete, and Snow's action was dictated solely by strong circumstantial evidence. As pointed out by Lawther¹⁰⁰: "An empirical approach to these problems must not be scorned while

fundamental data are sought; the only proper way to tackle a cholera epidemic is to wrench the handle off the Broad Street pump without waiting for the demonstration of the bacillus." In this connection we may bear in mind that even if legislation were enacted today, it would probably take at least ten years to begin having a significant effect upon emissions¹⁰¹.

It may be argued that Snow's simple experiment cannot be compared to the much more expensive, far-reaching experiment of reducing emissions from fossil-fuel combustion. However, another great experiment in London provides a more nearly comparable case. In 1952, when I was living there, the "Great Smog" killed between 2500 and 4000 people in a week, three or more times the normal death rate⁷⁵. No one -- to my knowledge -- contests that statement, yet the chain of causation has still not been completely worked out and was not at all clear at the time of the incident. The evidence was, like Snow's, largely circumstantial. Nevertheless, the government authorities acted on it and cleaned up the London air at great expense. I doubt that anyone now suggests they were wrong to conduct this expensive experiment, or that the regulations they issued ought to be rescinded.

We should remember that governments and industries regularly initiate far-reaching and extremely expensive social and economic programs on the basis of evidence not nearly as convincing as that available in the case of acid deposition, where we see major ecological damage already and expect much more serious effects if emissions are not curtailed. Is there any reason why action on environmental programs should require a weight of evidence far greater than is demanded of these other large-scale initiatives? If not, what are we waiting for? All our experience of environmental problems teaches us that if we wait until the last scintilla of evidence has been gathered to prove the entire chain of causation, we shall have waited too long, and thereby paid a price in severe damage to a fragile part of our vital life-support system here on the planet Earth.

REFERENCES

1. Smith, R.A. "On the Air and Rain of Manchester," Mem. Manchester Lit. Phil. Soc., Series 2, 10:207-217 (1852).
2. Smith, R.A. Air and Rain. (London: Longmans, Green, 1872), p. 600.
3. Gorham, E. "A Historical View of Interactions Between the Atmosphere and the Biosphere." Chapter 2 in Atmosphere-Biosphere Interactions, Toward a Better Understanding of the Ecological Consequences of Fossil Fuel Combustion (Washington, DC: National Research Council, 1981), pp. 9-21.
4. Cowling, E.B. "An Historical Resume of Progress in Scientific and Public Understanding of Acid Precipitation and Its Consequences," Research Report FR18/80 (Oslo, As: SNSF Project, 1981), p. 29.
5. Oden, S. "The Acidification of Air and Precipitation, and its Consequences in the Natural Environment," Ecol. Comm. Bull. No. 1, Nat. Sci. Research Council, Stockholm. (Arlington, VA: Translation Consultants, TR-1172).
6. Likens, G.E., F.H. Bormann, and N.M. Johnson. "Acid Rain," Environment 14:33-40 (1972).
7. Gorham, E. "Atmospheric Pollution by Hydrochloric Acid," Quart. J. Royal Meteorol. Soc. 84:274-276 (1958).
8. Gorham, E. "Acid Precipitation and Its Influence upon Aquatic Ecosystems -- a Review," Water Air Soil Poll. 6:457-481 (1976).
9. Engelmann, R.J., and G.A. Sehmel, Coordinators. "Atmospheric-Surface Exchange of Particulate and Gaseous Pollutants," U.S. ERDA Ser., CONF-740921 (Springfield, VA: Nat. Tech. Info. Service, 1974).
10. Galloway, J.N., S.J. Eisenreich and B.C. Scott, Eds. Toxic Substances in Atmospheric Deposition: A Review and Assessment. (National Atmospheric Deposition Program, NC-141, 1980), p. 146.
11. Galloway, J.N., G.E. Likens and E.S. Edgerton. "Hydrogen Ion Speciation in the Acid Precipitation of the Northeastern United States", Water, Air & Soil Poll. 6:423-433 (1976).
12. Dickson, W. "Properties of Acidified Waters". In: Ecological Impact of Acid Precipitation, D. Drabløs and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980), pp. 75-83.
13. Schindler, D.W., R.H. Hesslein, R. Wagiman and W.S. Broecker. "Effects of Acidification on Mobilization of Heavy Metals and Radionuclides from the Sediments of a Freshwater Lake," Can. J. Fish. Aquat. Sci. 37:373-377 (1980).

14. Lunde, G., J. Gether, N.Gjos, and M.-B.S. Lande. "Organic Micropollutants in Precipitation in Norway," Research Report, FR9/76 (Oslo, As: SNSF Project, 1976), p. 17.
15. Bottini, O. "Le Pioggie Caustiche Nella Regione Vesuviana," Ann. Chim. Applic. 29:425-433 (1939).
16. Hutchinson, T.C., W. Gizyn, M. Havas and V. Zobens. "Effects of Long-Term Lignite Burns on Arctic Ecosystems at the Smoking Hills, N.W.T. In: Trace Substances in Environmental Health, XII, D.D. Hemphill, Ed. (Columbia: U. of Missouri Press, 1979), pp. 317-332.
17. Hitchcock, D., L.L. Spiller and W.E. Wilson. "Sulfuric Acid Aerosols and HCl Release in Coastal Atmospheres: Evidence of Rapid Formation of Sulfuric Acid Particulates," Atmos. Envir. 14:165-182 (1980).
18. Likens, G.E., R.F. Wright, J.N. Galloway and T.J. Butler. "Acid Rain," Sci. Amer. 241:43-51 (1979).
19. Junge, C.D., and R.T. Werby. "The Concentration of Chloride, Sodium, Potassium, Calcium and Sulphate in Rain Water over the United States," J. Meteorol. 15:417-425 (1958).
20. Eriksson, E. "The Yearly Circulation of Chloride and Sulfur in Nature; Meteorological, Geochemical and Pedological Implications, Part II," Tellus 12:63-109 (1960).
21. National Research Council. Atmosphere-Biosphere Interactions: Toward a Better Understanding of the Ecological Consequences of Fossil Fuel Combustion, Chapter 5, Atmospheric Transport, Transformation, and Deposition Processes (Washington, DC: National Academy Press, 1981), pp. 57-86.
22. Shannon, D.G., and L.O. Fine. "Cation Solubilities of Lignite Fly Ashes," Envir. Sci. Tech. 8:1026-1028 (1974).
23. Barrett, E., and G. Brodin. "The Acidity of Scandinavian Precipitation," Tellus 7:251-257 (1955).
24. Lau, N.C., and R.J. Charlson. "On the Discrepancy between Background Atmospheric Ammonia Gas Measurements and Existence of Acid Sulfates as a Dominant Atmospheric Aerosol," Atmos. Envir. 11:475-478 (1977).
25. Junge, C.E. "The Distribution of Ammonia and Nitrate in Rain Water over the United States," Trans. Amer. Geophys. Union 39:241-248 (1958).
26. Robinson, E., and R.C. Robbins. "Gaseous Nitrogen Compound Pollutants from Urban and Natural Sources," Jour. Air Poll. Control Assoc. 20:303-306 (1970).
27. National Research Council, Ammonia. (Washington, DC: National Academy of Sciences, 1979), p. 384.

28. Growther, C. and A.G. Ruston. "The Nature, Distribution and Effects Upon Vegetation of Atmospheric Impurities in and near an Industrial Town," J. Agr. Sci. 4:25-55 (1911).
29. Gordon, A.G., and E. Gorham. "Ecological Aspects of Air Pollution from an Iron-Sintering Plant at Wawa, Ontario," Can. J. Bot. 41:1063-1078 (1963).
30. Gorham, E. "On the Acidity and Salinity of Rain," Geochim. Cosmochim. Acta 7:231-239 (1955).
31. Gorham, E. "The Influence and Importance of Daily Weather Conditions in the Supply of Chloride, Sulfate and Other Ions to Fresh Waters from Atmospheric Precipitation," Phil. Trans. Royal Soc. London, Series B, 247:147-178 (1958).
32. Gorham, E. "Free Acid in British Soils," Nature 181:152-154 (1958).
33. Bridge, J.E., and F.P. Fairchild. "Northeast Damage Report of the Long Range Transport and Deposition of Air Pollutants," Northeast Regional Task Force on Atmospheric Deposition (1981), p. 72.
34. Galloway, J.N., and D.M. Whelpdale. "An atmospheric sulfur budget for eastern North America," Atmos. Envir. 14:409-417 (1980).
35. Robinson, E., Husar, R.B., and Galloway, J.N. Sulfur Oxides (Washington, DC: National Academy of Sciences, 1978), pp. 18-62.
36. Chester, P.F. "Acid Rain, SO₂ Emissions and Fisheries," Central Electricity Research Laboratories, Lab Note No. RD/L/2122N81 (Leatherhead, Surrey, U.K., 1981), p. 8 with 13 figs.
37. Underwood, J.K. "pH of Precipitation and Annual Deposition of Excess Sulfate, Acidity and Nitrate on Nova Scotia," in Proceedings of a Workshop on Long Range Transport of Air Pollution and Its Impact on the Maritime Provinces, A.D.J. O'Neill, Ed. (Bedford, Nova Scotia: Atmospheric Environment Service, 1979), pp. 25-34.
38. Liljestrand, H.M., and J.J. Morgan. "Chemical Composition of Acid Precipitation in Pasadena, California," Envir. Sci. Technol. 12:1271-1273 (1978).
39. McColl, J.G., and D.S. Bush. "Precipitation and Throughfall Chemistry in the San Francisco Area," J. Envir. Qual. 7:352-357 (1978).
40. Fisher, D.W. "Annual Variations in Chemical Composition of Atmospheric Precipitation in Eastern North Carolina and Southeastern Virginia," U.S. Geol. Survey Water-Supply Paper 1535-M, p. 21 (1968).
41. Munger, J.W. "Chemistry of Atmospheric Precipitation in the Northcentral United States: Influence of Sulfate, Nitrate, Ammonia and Calcareous Soil Particulates," Atmos. Envir. (in press).

42. Reuss, J.O. "Chemical/Biological Relationships Relevant to Ecological Effects of Acid Rainfall," USEPA Report - EPA-660/3-75-032 (1975), p. 45.
43. Brimblecombe, P. "London Air Pollution, 1500-1900," Atmos. Envir. 11:1157-1162 (1977).
44. Brimblecombe, P. "Air Pollution in Industrializing England," J. Air Poll. Control Assoc. 28:115-118 (1978).
45. Koide, M., and E.D. Goldberg. "Atmospheric Sulfur and Fossil Fuel Combustion," J. Geophys. Res. 76:6589-6596 (1971).
46. Hansen, D.A., and G.M. Hidy. "Review of Questions Concerning Rain Acidity Data," Atmos. Envir. (in press).
47. Siebel, E.P., and R.G. Semonin. "Acid Rain: What Do We Know?," Illinois Institute of Natural Resources, State Water Survey Division (Champaign, Illinois, 1981), p. 11.
48. Likens, G.E., and T.J. Butler. "Recent Acidification of Precipitation in North America," Atmos. Envir. 15:1103-1109 (1981).
49. Cohen, J.B. and A.G. Ruston. Smoke. (London: Arnold, 1912), p. 88.
50. Parker, A. "Report on the Investigation of Atmospheric Pollution," Department of Scientific and Industrial Research, Report No. 27 (London: Her Majesty's Stationery Office, 1955), p. 207.
51. Houghton, H. "On the Chemical Composition of Fog and Cloud Water," J. Meteorol. 12:355-357 (1955).
52. Gorham, E., and A.G. Gordon. "The Influence of Smelter Fumes upon the Chemical Composition of Lake Waters near Sudbury, Ontario, and upon the Surrounding Vegetation," Can. J. Bot. 38:477-487 (1960).
53. McLean, R.A.N. "Relative Impact of Sulfur and Nitric Acid," Shield Lakes Acidification Network Telegraph (1981), pp. 15-16.
54. Gorham, E. "The Ionic Composition of Some Lowland Lake Waters from Cheshire, England," Limnol. Oceanogr. 2:22-27 (1957).
55. Mackereth, F.J.H. "Chemical Analysis in Ecology Illustrated from Lake District Tarns and Lakes. 1. Chemical Analysis," Proc. Linn. Soc. London 167:159-164 (1957).
56. Galloway, J.N., C.L. Schofield, G.R. Hendrey, N.E. Peters and A.H. Johannes. "Sources of Acidity in Three Lakes Acidified During Snowmelt". In: Ecological Impact of Acid Precipitation, D. Drabløfs and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980), pp. 264-265.
57. Galloway, J.N., C.L. Schofield, G. R. Hendrey, E.R. Altwicker and D.E. Troutman. "An Analysis of Lake Acidification Using Annual Budgets". In: Ecological Impact of Acid Precipitation, D. Drabløfs and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980) pp. 254-255.

58. Schindler, D.W. "Experimental Acidification of a Whole Lake: a Test of the Oligotrophication Process." In: Ecological Impact of Acid Precipitation, D. Drabløis and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980) pp. 370-374.
59. Drabløis, D., and A. Tollan, Eds. Ecological Impact of Acid Precipitation, (Oslo, As: SNSF Project, 1980) p. 383.
60. Muniz, I.P., and H. Leivestad. "Toxic Effects of Aluminium on the Brown Trout, Salmo trutta L." In: Ecological Impact of Acid Precipitation, D. Drabløis and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980) pp. 320-321.
61. Yoshimura, S. "Kata-numa, a Very Strong Acid-Water Lake of Volcano Kata-numa, Miyagi Prefecture, Japan," Arch. Hydrobiol. 26:197-202 (1933).
62. Yoshimura, S. "Lake Akanuma, a Siderotrophic Lake, at the Foot of Volcano Bandai, Hukusima Prefecture, Japan," Proc. Imp. Acad. Tokyo 11:426-428 (1935).
63. Ohle, W. "Der schwefelsaure Tonteich bei Reinbeck, Monographie eines idiotrophen Weihers," Arch. Hydrobiol. 30:604-662 (1935).
64. Abrahamsen, G. "Acid Precipitation, Plant Nutrients and Forest Growth." In: Ecological Impact of Acid Precipitation, D. Drabløis and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980), pp. 58-63.
65. Tamm, C.O. "Acid Precipitation: Biological Effects in Soil and on Forest Vegetation," Ambio 5:235-238 (1976).
66. Salisbury, E.J. "Stratification and Hydrogen-Ion Concentration of the Soil in Relation to Leaching and Plant Succession with Special Reference to Woodlands," J. Ecol. 9:220-240 (1922).
67. Iversen, J. "The Late-Glacial Flora of Denmark and Its Relation to Climate and Soil". In: Studies in Vegetational History in Honour of Knud Jessen, Geol. Survey Denmark, Series II, No. 80 (1954), pp. 87-119.
68. Gorham, E., P.M. Vitousek and W.A. Reiners. "The Regulation of Chemical Budgets over the Course of Terrestrial Ecosystem Succession," Ann. Rev. Ecol. Syst. 10:53-84 (1979).
69. Overrein, L., H.M. Seip, and A. Tollan. Acid Precipitation -- Effects on Forest and Fish, Research Report FR 19/80 (Oslo, As: SNSF Project, 1980), p. 175.
70. Ulrich, B., R. Mayer and P.K. Khanna. "Chemical Changes Due to Acid Precipitation in a Loess-Derived Soil in Central Europe," Soil Sci. 130:193-199 (1980).
71. Tomlinson, G.H. "Die-back of Forests -- Continuing Observations," Research Memorandum, Project No. 74-7124-13, Rept. #2. (Senneville, Quebec: Domtar Research Centre, 1981), p. 17.
72. Johnson, A.H., T.G. Siccama, D. Wang, R.S. Turner and T.H. Barringer. "Recent Changes in Patterns of Tree Growth in the New Jersey Pinelands: A Possible Effect of Acid Rain," J. Envir. Qual. 10:427-430 (1981).

73. Nriagu, J.O. "Deteriorative Effects of Sulfur Pollution on Materials." In: Sulfur in the Environment II. Ecological Impacts, J.O. Nriagu, Ed. (New York: Wiley, 1978), pp. 1-59.
74. Hultberg, H., and A. Wenblad. "Acid Groundwater in Southwestern Sweden," In: Ecological Impact of Acid Precipitation, D. Drabløs and A. Tollan, Eds. (Oslo, As: SNSF project, 1980), pp. 220-221.
75. Hamilton, L.D. "Health Effects of Acid Precipitation," in Proceedings, Action Seminar on Acid Precipitation (Toronto: A.S.A.P. Organizing Committee, 1979), pp. 117-134.
76. Speizer, F.E., and B.G. Ferris, Jr. "Epidemiologic Studies of Health Effects of Sulfur Oxides." In: Sulfur Oxides. (Washington, DC: National Academy of Sciences, 1978), pp. 180-209.
77. Jacobson, J. "Experimental Studies on the Phytotoxicity of Acid Precipitation: the United States Experience." In: Effects of Acid Precipitation on Terrestrial Ecosystems, T.C. Hutchinson and M. Havas, Eds. (New York: Plenum, 1980), pp. 151-160.
78. Cowell, D.W., A.E. Lucas and C.D.A. Rubec. "The Development of an Ecological Sensitivity Rating for Acid Precipitation," Working Paper No. 10, Lands Directorate, Environment Canada, p. 42.
79. Almer, B., W. Dickson, C. Ekstrom and E. Hornstrom. "Sulfur Pollution and the Aquatic Ecosystem". In: Sulfur in the Environment, Part II: Ecological Impacts, J.O. Nriagu, Ed. (New York: Wiley, 1978), pp. 271-311.
80. Vallentyne, J.R. The Algal Bowl: Lakes and Man. (Ottawa: Information Canada, 1974), p. 186.
81. Poundstone, W.N. Some Facts About Acid Rain (Washington, DC: National Coal Association, 1980), p. 16.
82. Katzenstein, A.W. "An Updated Perspective on Acid Rain," Edison Electric Institute (1981), p. 43.
83. Comptroller General of the United States. "The Debate Over Acid Precipitation -- Opposing Views -- Status of Research," U.S. General Accounting Office EMD-81-131 (1981), p. 44.
84. Carter, J. "The President's Environmental Program 1979," The President's Council in Environmental Quality (Washington, DC, 1981), p. 57.
85. Wetstone, G.S. "The Need for a New Regulatory Approach," Environment 22:9-14 and 40-43 (1980).
86. Subcommittee on Acid Rain, Standing Committee on Fisheries and Forestry, House of Commons, Canada. "Still Waters," Minister of Supply and Services Canada, Cat. No. XC 29-321/2-01E (Ottawa, Ontario, 1981), p. 150.

87. Dillion, P.J., N.D. Yan, W.A. Scheider and N. Conroy. "Acidic Lakes in Ontario, Canada: Characterization, Extent, and Responses to Base and Nutrient Additions," Ergebn. Limnol. 13:317-336 (1979).
88. Edman, G., and S. Fleischer. "The River Hogvadsan liming project -- a presentation." In: Ecological Impact of Acid Precipitation, D. Drabløs and A. Tollan, Eds. (Oslo, As: SNSF Project, 1980), pp. 300-301.
89. Roberts, J. "The Canadian View," Canada Today 12(2):6 (1981).
90. National Commission of Air Quality. "To Breathe Clean Air" (Washington, DC: Superintendent of Documents, 1981), p. 118.
91. Evans, L.S., G.R. Hendrey, G.J. Stensland, D.W. Johnson and A.J. Francis, "Acidic Precipitation: Considerations for an Air Quality Standard," Water, Air, Soil Pollution 16:469-509 (1981).
92. Glass, G.E., and O.L. Loucks. "Impacts of Airborne Pollutants on Wilderness Areas Along the Minnesota-Ontario Border," U.S. EPA Ser., EPA-600/3-80-044 (Springfield, VA: Nat. Tech. Info. Service, 1980), p. 187.
93. Thornton, J.D., S.A. Heiskary, R.D. Payer and J. Matta. "Acid Precipitation in Minnesota," Report to the Legislative Commission on Minnesota Resources, Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, and Minnesota Department of Health (1981), p. 331.
94. Underwood, J.K. "Acidic Precipitation in Nova Scotia," Nova Scotia Dept. of the Environment (Halifax, N.S., 1981), p. 17 + 7 figs.
95. Johannes, A.H., and E. Altwicker. "Atmospheric Inputs to Three Adirondack Lake Watersheds". In: The Integrated Lake-Watershed Acidification Study, Electric Power Research Institute EA-1825, Project 1109-5 (Palo Alto, CA, 1981), pp. 3.1-3.13.
96. Environment Canada, "Downwind, the Acid Rain Story," Minister of Supply and Services Canada, Cat. No. En 56-56/1981 E (Ottawa, Ontario, 1981), p. 20.
97. Kerr, R.A. "Pollution of the Arctic Atmosphere Confirmed," Science 212:1013-1014 (1981).
98. Maize, K. "Acid Rain: Maybe the Midwest Is Not the Guilty Party After All," The Energy Daily (26 January 1982), pp. 5-6.
99. Thomas, K.B. "Snow, John," Dict. Sci. Biogr. 12:502-503 (1975).
100. Lawther, P.J. "Breathing Dirty Air," Medical World (September 1956), pp. 1-4.
101. Bachmann, J. Statement at U.S. EPA Acidic Deposition Ecological Effects Research Peer Review, North Carolina State University, Raleigh, NC (9-12 Feb. 1982).

REPORT OF THE WORKSHOP ON RESEARCH NEEDS

The following is a summary of the Research Needs Workshop that was chaired by Professor Eville Gorham of the University of Minnesota. The objective of this workshop was to identify the basic issues that must be addressed by scientific research as policies are being formulated to prevent acid rain. The narrative below is divided into the four main subtopics discussed at the conference: Biological/Ecological Effects, Transport, Deposition, and Emissions. Some general considerations brought under discussion are also included, and the summary concludes with four major recommendations.

Biological/Ecological Effects

The participants urged more research in several areas related to biological and ecological effects. With regard to aquatic ecosystems, it was recommended that more data --obtained by standardized survey techniques with a high degree of quality assurance -- are needed to determine the following: dose/response functions for surface and groundwater pH versus sulfate and nitrate loading; biological consequences of declining lake pH -- especially with regard to early warning of subacute and chronic effects; and the interaction of acids with various metals and nutrients. Several aspects of acid release occurring during the spring snowmelt were noted as needing more research. For instance, the relative importance of sulfate as nitrate, the consequences for aquatic and terrestrial organisms with special reference to embryonic defects, the significance of the pH shock as compared to long-term acidification, and the importance of metal mobilization during these periods were identified as issues requiring additional research. The time frame for lake acidification by (and recovery from) various degrees of acid loading is also a very important

subject requiring greater research effort. Further attention ought to be paid to paleoecological studies (e.g., diatom stratigraphy). An important question that was repeatedly brought under discussion was: "Can nitrate be given less attention than sulfate as an acid-related anion because it is consumed to a much greater degree by biological processes?" The consensus was that there is insufficient information to permit the importance of nitrate to be downplayed in present research.

There is need for more research on forest ecosystems, including such topics as: development and mapping of better indices to site sensitivity, effects of acidification on forest growth, interactions of acids with heavy metals and nutrient cycles in the soil, and the significance of particle impaction and throughfall. Long-term baseline studies of forest "health" should be initiated in sensitive areas likely to be affected in the future. More research, employing "calibrated watersheds" and experimental acidification, was also suggested.

The lack of research on wetlands and "brown-water" bog lakes was pointed out; both sorts of ecosystem should be included in future chemical and biological studies. With regard to the latter, it was noted that a scarcity of trained taxonomists may hinder sophisticated studies of plant and animal communities in these and other ecosystems.

The participants saw a need for further research on the possible human health effects of a broad spectrum of atmospheric pollutants (including acid sulfates) over a wide range of ambient levels. The subject is highly controversial, and more and better data are urgently needed.

The observation was made that there is a need for archives of various kinds of samples (e.g., organisms, soils, sediments, etc.). A workshop should be arranged in the near future to consider the materials to be archived, methods of sample collection and preservation, and the agencies that should perform this task.

Transport

Several topics related to the transport of pollutants were discussed. An important question was raised regarding the attention that should be given to the role of oxidants and metal catalysts in the production of sulfate and nitrate and, in particular, their effect on the distances these pollutants travel before deposition.

The use of multi-element descriptors to track pollutants from source to receptor was supported by the participants. It was the view of some participants that despite public aversion, radioactive isotopes added to emission plumes would prove to be the best tracers. If radioactive tracers proved too controversial, certain tracer gases were also suggested. Signatures for natural sources would also have to be considered.

The hope was expressed that new studies of atmospheric chemistry, dry deposition, and tracers will assist in the development of long-range transport models. Due consideration should be paid to meteorological conditions along the transport path from source to receptor, particularly during tracer experiments in developing the models. On the other hand, it was suggested that short-term needs for information on the dose side of dose/response calculations can be met by a more climatological approach to atmospheric transport and deposition.

One participant proposed a 4-5 year program of coal washing and the use of low-NO_x burners, combined with a national program of atmospheric and effects research that would yield information leading to more effective control measures. The focus of the atmospheric research would be upon the reductions in deposition that would result -- in different geographic regions -- from specific reductions in emissions inside and outside those same regions. In general, the panel declined to endorse this approach, and the consensus was that researchers should only determine the emission reductions necessary, leaving the method of reduction to be decided by others.

Deposition

Many participants suggested that there is an urgent need to know whether we can simplify dose/response studies by relying on readily measured "wet deposition" or "bulk deposition." To this end, the balance between wet and dry deposition should be determined at a broad range of sites. Such studies would consider the distance from sources, different climatic regimes, and the chemical environment in which the emission takes place. Better measurements of dry deposition are also needed for several pollutants and surfaces. In addition, improved capabilities for relating emission reductions to deposition reductions at given sites are essential. Modelling, which should be considered as one of several tools in analyzing the relative merits of control strategies, must be improved to include a range of interacting pollutants and to deal with non-linear reaction sequences.

Another very important question discussed by the panel was whether or not we need to be concerned with the forms of sulfur and nitrogen deposited at a site, or whether it can be assumed that all sulfur and nitrogen compounds will eventually have an acidifying influence. Such an assumption would greatly simplify the task of monitoring the relationship between deposition and acidification. In the monitoring process, it was the viewpoint of some of the participants that more attention must be paid to near-source deposition, which may be more important than is commonly believed.

Emissions

There was considerable concern that more attention should be focused on acquiring a better understanding of the overall costs of atmospheric reductions, including costs to future generations, and the costs and benefits assignable to different political jurisdictions. Similarly, it was suggested that the economic benefits of various control strategies be

examined more thoroughly, balancing the costs of control against the costs of no control. Members of the panel noted that both stationary and mobile sources should be considered, and that local effects -- such as materials damage, or possible harm to health -- should be addressed in addition to the chronic ecological effects of long-range transport.

It was also remarked that innovative, high-efficiency combustion technologies deserve a high research priority, and that we need better analyses of the costs and consequences of the disposal or recycling of the products of combustion.

General Considerations

It was observed that in view of the magnitude of environmental damages and the high cost of controls, and in view of the need to address the issues of acid rain and other environmental problems in a rational manner, it is essential that expertise and research staff of the highest caliber be maintained and developed fully in our scientific institutions. It is also essential that the diverse groups of scientists and non-scientists involved in the acid rain problem share their efforts, avoid duplication, integrate programs, and inform the general public in a variety of ways as to where we are going, and why. In the determination of policy and its implementation, decision-makers ought to distinguish clearly between unreviewed and unverified data in the "grey literature" and data in the peer-reviewed scientific literature.

A question was raised concerning the substitution of an annual general symposium on acid rain for the diverse meetings now taking place. The general consensus was that this would be a mistake. Major symposia are being organized every two or three years to report and synthesize the scientific research on acid rain, while other major meetings are considering broader, policy-related issues. The many smaller meetings -- each with its own special focus -- are also valuable, despite some overlap and duplication.

Major Conclusions and Recommendations

It was the sense of the workshop participants that the following four recommendations should be weighed seriously in the formulation of acid rain control strategies and research programs:

1. Because serious damage is already occurring, and more can be anticipated, emission abatement should start now, with refinement of goals to take place as abatement takes effect and research progresses. We should not wait to determine the optimal balance between SO_x and NO_x reduction before controls are initiated, but the balance should be a major focus for research.
2. The balance of opinion suggests that SO_x reductions ought to be the major focus initially but, where feasible, NO_x should also be controlled. For technical and economic reasons it is essential that flexibility be allowed when reductions are assigned to individual sources or groups of sources. The use of such flexibility should not, however, compromise environmental benefits.
3. There was general agreement that we should oppose strongly the tendency to view acid rain in isolation from the gaseous precursors and other pollutants associated with the combustion of fossil fuels (i.e., SO_x , NO_x , hydrocarbons, ozone, particulates, trace metals and organic micropollutants) because:
 - a. They are all part of the general air pollution impact of fossil fuel combustion.
 - b. There are strong possibilities for synergistic interactions.
 - c. Control strategies should be designed to cope with the mix of pollutants and not with isolated components.

4. In addition to the operation of many short-term research programs, a major effort must be devoted to setting up long-term monitoring -- on selected sites -- of the geochemical and biological consequences of ecosystem acidification.

Finally, a consensus was reached that it is not currently possible to select a few specific proposals that will deal with the many questions that need to be answered. Research must continue to go forward on a broad front.