Acid Rain: Biological Effects and Implications

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By Roger W. Ferenbaugh*

INTRODUCTION

Because of the controversy over air pollution that has erupted in newspapers and magazines during the past several years, most people are aware of the potential hazards associated with air pollutants such as sulfur dioxide, nitrogen oxides, ozone, etc. However, there is another, relatively unknown, type of air pollution which is just as serious, if not more serious, than anything of which the public is aware. This pollution goes by the name of "acid rain."

Acidity of rainwater is measured in terms of units called pH units. Neutral water, neither acid nor alkaline, has a pH of 7.0. Water of pH 6.0 is ten times as acid as neutral water; water of pH 5.0 is one hundred times as acid as neutral water; and so forth. Each decrease of one pH unit represents a ten-fold increase in acidity over the next higher pH value. If neutral water, with a pH of 7, is brought into contact with the atmosphere, it begins to absorb carbon dioxide. The dissolution of carbon dioxide in water produces a weak acid called carbonic acid. Water which has absorbed all of the carbon dioxide it can hold at normal atmospheric temperature and pressure has a pH of about 5.7. And in fact, rainwater collected in areas where pollution is negligible can be expected to have a pH of about this value.

In some parts of the world, however, researchers have discovered that rainwater is more acidic than is to be expected from the dissolution of carbon dioxide alone. In the Scandinavian countries and in the northeastern portion of the United States, rainwater consistently has a pH in the range of 3.0 to 4.0.1 In the United States, values as low as 2.1 have been recorded.3

The primary component of acid rain appears to be sulfuric acid, formed from sulfur dioxide by a series of complex photochemical and catalytic reactions.3 Recent studies indicate that nitric acid, formed from the oxidation of nitrogen oxides by ozone, may also be
significant. Other acids (such as hydrofluoric) may be locally significant if there is an emission source in the area. The acid rain in Scandinavia probably results from industrial emissions in Great Britain and industrialized regions of Europe, while acid rain in New England results from emissions in the heavily industrialized eastern portion of this country.

One obvious consequence of acid rain is its corrosive effect on exposed stone and metal structures, but there are also many biological effects which are not so obvious. These biological effects are summarized below.

I. BIOLOGICAL EFFECTS OF ACID RAIN

A. Terrestrial Mammalian Animals

Acid rain, as such, does not have much direct effect on land animals. However, when atmospheric conditions are right for the occurrence of large-scale inversion layers, acid aerosol smogs can form. These smogs can have an effect on mammalian respiratory systems.

Industrial exposures and experiments with laboratory animals have shown that the effect of high concentrations of acid aerosol is bronchoconstriction and laryngeal spasm, leading to death by suffocation. Prolonged exposure to concentrations of acid not strong enough to cause immediate death results in pathological lesions within the lungs. Size of the aerosol particles also has an effect. Larger particles tend to settle out before reaching the lungs and cause constrictions of bronchial passages, whereas smaller particles penetrate into the lungs themselves.

Concentrations of aerosol high enough to cause these effects, however, are not normally encountered in the environment, even under inversion conditions. The lower concentrations which could possibly be encountered in the environment would have more subtle effects. Such concentrations, although not high enough to cause complete bronchoconstriction, would cause some swelling of the bronchial walls and thus would increase the resistance to air flow through the bronchial passages. There would also be effects on the lungs themselves.

Mammalian lungs are subdivided into small compartments called alveoli. The oxygen in inhaled air is exchanged for the carbon dioxide in the blood across the surfaces of the epithelial cells that line the alveoli. Particulate matter and bacteria which enter the lungs with incoming air are ingested by specialized scavenger cells that creep around the alveoli.
Upon the death of these scavenger cells, they are collected in a mucus layer which is moved from the lungs to the esophagus by a layer of filamentous projections (cilia) from the cells lining the trachea. There are two possible effects that acid rain may have upon this system. One is that the efficacy of the scavenger cells and cilia may be impaired. Although this has never been specifically demonstrated for acid aerosol, it is known to occur as a result of exposure to sulphur dioxide. The other effect is that hypertrophy (enlargement) of the epithelial cells lining the alveoli may occur, resulting in an emphysema-like condition which would interfere with the exchange of oxygen.

Both the increased resistance to air intake and the hypertrophy of alveolar epithelial cells would be expected to have the greatest effect on asthmatics, elderly persons, and others with chronic respiratory conditions. These individuals are particularly affected when acid smogs accumulate during inversion conditions, and attempts have been made to correlate the occurrence of inversion conditions with hospital admittances for persons in respiratory distress. Such studies have shown some positive correlation. Acute smog episodes, probably involving acid aerosols, which occurred earlier in this century in the Meuse Valley, Belgium; Donora, Pennsylvania; and London, England killed many people.

B. Aquatic Systems

Because aquatic systems are collection points for rainwater, the acidity of these systems may be drastically altered by acid rainfall. This has been substantiated by studies in Sweden and Norway. In a five year study (1965-1970) of fifteen rivers in Sweden, the pH dropped in all fifteen. Not one instance of pH increase was noted. In a later study of nearly four hundred lakes, all were found to have been acidified to some extent; many to a degree which resulted in significant biological changes within the lakes. It is true that many of the lakes in Sweden are of a type that lacks buffering capacity (which may be defined as the capacity to maintain a constant pH by neutralizing any acid or alkaline substances which enter the water), but even the highly buffered lakes have undergone a reduction in pH. Furthermore, the melting of polluted snow in the spring can send a surge of acidified water into the lakes, resulting in a sudden drop in pH.

Acidification of aquatic systems has several biological effects, some of the most obvious being those on fish. These effects may include a decrease in resistance to disease and toxic materials, a
decrease in general vitality, changes in migratory and spawning behavior, and mild to severe effects on the development and viability of eggs.\textsuperscript{21} As the pH falls, existing fish populations fail to reproduce. This failure is probably aggravated by the previously noted pH drop in the spring which occurs during the spawning season for some species. Eventually the non-reproducing population is replaced by more tolerant species, and ultimately all fish will disappear if conditions become adverse enough.\textsuperscript{22} Such changes would have obvious repercussions on fresh-water fishing industries.\textsuperscript{23}

Increased acidity may also cause changes in the types of invertebrate animals and algae which are present,\textsuperscript{24} and this would have an additional effect on the fish population because of the change in available food sources. Snails, crayfish, and certain other invertebrate animals are particularly sensitive to acidified water and rapidly disappear as the pH is lowered.\textsuperscript{25} In general, the species diversity (\textit{i.e.}, the number of different types) of both invertebrate animals and algae decreases.\textsuperscript{26} Those species which are left are likely to be the more undesirable types, such as blue-green algae, which may secrete toxins or impart bad taste and odor to the water.

It has been suggested that acidification of aquatic systems be offset by liming the lakes. However, liming on such a scale would not only be prohibitive in terms of the amount of lime required, but also could have entirely unforeseen environmental consequences.\textsuperscript{27}

\section*{C. Soil Systems}

Although most plants produce their own food through the process of photosynthesis, they are also vitally dependent on the soil in which they grow for the provision of necessary minerals and chemical elements. The soil acts as a reservoir for these nutrients. The origin of the nutrients may be either weathering of parent rock or absorption from the atmosphere; but once the nutrients have been introduced into the soil, they are continuously recycled through plants and animals back to the soil in the form of dead organic material. Plants take up the nutrients through their root systems, and animals eat either plants or other animals which have eaten plants.

Nutrients, however, do not always enter the soil in forms which can be directly used by plants. Often chemical transformations must take place. For example, dead organic material must be broken down by decay organisms (primarily bacteria and fungi) that live in the soil in order to release the nutrients contained in the organic matter. Nitrogen, another necessary chemical element, is
replenished in the soil by microorganisms which extract ("fix") it from the atmosphere. After being fixed, the nitrogen must undergo a series of chemical transformations, each step of which is mediated by a different microorganism.

The effect of acid rain on this system could be either to suppress microbial activity entirely or else to enhance the activity of some microorganisms while repressing the activity of others. Nitrogen-fixing blue-green algae, for example, cease to function below a pH of 6. Thus shortages of some nutrients may occur because the nutrients are accumulating in the soil in forms which are unavailable to plants or because they are not entering the soil at all.

Acid rain may also affect the storage function of the soil. When nutrients, either by chemical weathering or microbial action, enter the soil in forms which can be used by plants, they are prevented from being immediately washed out because they are electrostatically bound to the surface of soil particles. Acidity in rain increases its ability to break electrostatic bonds, thus making acid rain more effective in leaching these nutrients from the soil and washing them away. An investigation into the leaching of calcium by acid rain showed that soils which are naturally alkaline because of their limestone or dolomite content have a high capacity for neutralizing acid rain. Forest soils, however, are usually of a more acidic type and therefore are more susceptible to leaching.

It has been suggested that the leaching effects of acid rain might be offset by enhanced chemical weathering, also caused by the acid. A study was carried out in New England to determine if this was indeed happening, but no increase in chemical weathering could be detected.

The ultimate effect of both the interference with microbial activity and the leaching of nutrients is to reduce the availability of these nutrients to plants. In this way, continued acid rainfall will eventually reduce plant productivity. (For the purposes of this discussion, productivity may be defined as the amount of biomass, or weight, that a plant gains per unit of time.) Forests, because of their more acidic soil, are most susceptible to this productivity loss.

As in the case of aquatic systems, liming of forest lands has been proposed, with the implication that such liming would offset the adverse effects of acid rain by neutralizing it. However, not only would this seem to be impractical on the scale required, but there is also the possibility of unforeseen long-term ecological effects.
D. Plants

Secondary effects of acid rain on vegetation in the form of reduced nutrient availability have already been discussed. However, acid rain can also have two kinds of direct effects on the plants themselves: effects on development, and effects on physiological (i.e., metabolic or biochemical) processes.

All organisms undergo a period of development, during which various portions of the embryonic tissue that forms after fertilization of an egg become specialized for specific functions (e.g., liver tissue, bone tissue, etc.). In vertebrate animals, development ceases early in the life of the individual, after which occurs only growth, or increase in size, until the animal is full-grown. Plants, however, differ from animals in that they retain portions of embryonic tissue throughout their lives. This embryonic tissue is found within the buds of plants and is responsible for the formation of new leaves and flowers for as long as the plants live. Embryonic tissues are particularly vulnerable to injury by acid rain, and the degree of vulnerability depends upon the extent to which the embryonic tissue is protected. Pine trees and yellow birch are two examples of plants in which gross deformation results from exposure to acid rain. In pines this takes the form of shortened needles, and if large numbers of the short needles occur, the photosynthetic capacity of the trees is greatly reduced. This reduces their general vitality and their chances for survival.

The other effects of acid rain on plants are physiological. Leaching of nutrients from the soil has already been noted as an effect of acid rain. A similar leaching of nutrients from plant tissues themselves can occur as the acid rainwater flows over the plant surfaces. More important, however, are the effects of acid rain on the photosynthetic processes.

Photosynthesis is the process by which plants convert the energy of sunlight into stored chemical energy in the form of carbohydrate foodstuffs (sugars and starches). Within the plant body, the green pigment chlorophyll is responsible for the capture of the energy of sunlight. It has been known for some time that if chlorophyll is extracted from plant tissue and placed in an acidic environment, it is “bleached.” That is, it is changed into a chemical form which is no longer able to capture the energy of sunlight. However, the data on whether or not acid rain can bleach chlorophyll within intact plant tissues are conflicting. Treatment of moss with simulated acid rain did cause a reduction in chlorophyll content, whereas treatment of beans with simulated acid rain had no effect on chlorophyll
content at all.\textsuperscript{39}

In addition to possible interactions with chlorophyll, acid rain interferes with photosynthesis in other ways. The carbohydrate-producing capacity of bean plants treated with acid rain is greatly reduced, and consequently the productivity of these plants is less than that of plants not subjected to the acid treatment.\textsuperscript{40}

There is also a report that acid rain may interfere with plant reproduction by affecting the growth of certain reproductive structures, but it is uncertain whether this effect is due solely to acid rain.\textsuperscript{41}

In conclusion, plants quite probably exhibit different degrees of susceptibility to the effects of acid rain. If a plant is covered by an impervious cuticle or is otherwise protected, then it is less susceptible to acid effects than if it were not protected.

\section*{II. Ecological Effects of Acid Rain}

Ecologists are concerned about the effects of acid rain (as well as other pollutants) on the environment not only because of the gross direct damage which it may cause, but also because of subtle changes in biological relationships which may result. One of these changes may be a gradual decline in plant productivity. Early in this century an experiment was conducted in which plots of timothy grass were treated with sulfuric acid solutions in a pH range of 2.2 to 3.7.\textsuperscript{42} The experiment was continued for a period of three years. At the end of this time, the grass in the plots subjected to the more acidic treatments was dead, and even the least acidic treatments had caused a decrease in productivity.

As a result of the increased acidity of rainfall, the U.S. Environmental Protection Agency has estimated that certain Scandinavian forests may experience a 10-15\% decline in productivity by the year 2000,\textsuperscript{43} and Whittaker \textit{et al.}\textsuperscript{44} feel that a significant decline in the productivity of deciduous forests in the northeastern United States may already have taken place. Such a decline would obviously be detrimental to forest products industries, which are already in trouble because of dwindling forest reserves. Furthermore, there has been speculation that if the acid rain phenomenon becomes any worse, the result may be a decline in the productivity of grains and other crops.\textsuperscript{45} Since there is currently great concern over what seems to be an increasing shortage in world food supply, and since the entire world food supply depends, either directly or indirectly, on plant productivity, the prospect of a decline in productivity because of an increase in the acidity of rainfall is not to be taken lightly.
Moreover such a decline is quite conceivable in terms of the acid rain effects previously discussed. Plant productivity is dependent upon the photosynthetic production of carbohydrates, and it has already been noted that simulated acid rain interfered with the carbohydrate-producing capacity of bean plants. Additional productivity losses could be caused by nutrient loss from the soil. In either case, seeds, fruits, roots, tubers, etc., which are the plant parts most often used as food and which are organs of carbohydrate storage, are likely to be significantly affected by any decrease in carbohydrate production.

What is the likelihood that acid rain will become any more serious a problem than it already is? Since the acidity of rainfall is largely dependent on the amount of sulfur dioxide discharged into the atmosphere, the answer to this question depends on the changes, if any, made in the air quality standards of the Environmental Protection Agency. The following table summarizes the existing standards.48

**Primary Standards**

- Annual Arithmetic mean—0.03 ppm (parts per million)
- Maximum 24-Hour Concentration—0.14 ppm, not to be exceeded more than once per year.

**Secondary Standards**

- Annual Arithmetic Mean—0.02 ppm.
- Maximum 24-Hour Concentration—0.1 ppm, not to be exceeded more than once per year.
- Maximum 3-Hour Concentration—0.5 ppm, not to be exceeded more than once per year.

The primary standard is defined as “allowing an adequate margin of safety” in protecting the public health, whereas the secondary standard protects the public “from any known or anticipated adverse effects” i.e., not necessarily health effects.

In its report to the United Nations, the Swedish Preparatory Committee recommended approximately the same standards.47 In order to limit effects on human health, the maximum average monthly standard was recommended to be 0.05 ppm, while a maximum of 0.02 ppm was recommended for the avoidance of damage to sensitive trees. Some investigators who have worked with acid rain feel that the standards should be more stringent. And yet, there are strong possibilities that air quality standards could be relaxed rather than tightened.
In a recent discussion of sulfur dioxide standards, it was pointed out that most areas of the United States may easily meet the existing air quality standards, with offensive pollution only occurring around certain heavily industrialized and/or urbanized areas. The conclusion was that perhaps the standards should be re-examined to see if they really need to be as stringent as they are. Other people flatly assert that the sulfur dioxide problem is overstated and that therefore a massive commitment to clear up emissions is unnecessary. This type of argument is advanced to justify the use of "tall stacks" to more effectively disperse sulfur dioxide emissions and thus reduce local concentrations. However, while better dispersion may alleviate the immediate problem, the sulfur dioxide is still introduced into the atmosphere where it can be converted into sulfuric acid, perhaps (as in the case of Scandinavia) to fall in regions far removed from the point of emission.

The current energy crisis has also brought forth suggestions that air quality standards be relaxed, albeit on different grounds. The argument runs that energy production should be fostered and increased, and one way to increase production is by eliminating the need for expensive pollution control equipment and by allowing the use of the more abundant and readily accessible high-sulfur fuel. Thus there is considerable pressure for the relaxation of air quality standards. However, the advisability of doing so should still be dependent on the amount of environmental damage that would result, and as yet there is no adequate way of estimating the potential damage.

III. Possible Solutions

Is it possible to remove sulfur compounds from stack gases before the gases are emitted into the atmosphere? Several assessments of the available technology have recently been made, and several approaches to the problem are under investigation. These methods involve various types of neutralization, scrubbing, or absorption processes. Most of the processes are still in the pilot-plant or prototype stages, but a few full scale installations have been made. Most of these are operating at 95% or better efficiency with 95% or better removal of sulfur compounds, but there are still problems associated with sulfur removal. Considering the volumes of stack gases emitted, even one or two percent of sulfur not removed is a significant amount over a year's time. Furthermore, the removal of the last few percent of sulfur is said to be prohibitive both in terms of equipment required and cost of removal.
Even supposing that complete removal could be effected, there would still remain the problem of what to do with the sulfurous byproducts. The byproducts of some of the removal processes are useless and must be disposed of. Use as landfill or simply dumping the material in an unused area is not feasible because of the tremendous quantity involved. Other processes generate usable forms of sulfur, such as elemental sulfurs, sulfuric acid, or gypsum. The problem here is that the supply of materials so generated would flood the markets. Several exotic uses for sulfur, such as roadbed material or building blocks, have been proposed, but it will be a long time, if ever, before a significant amount of sulfur is demanded for these uses. Several uses for sulfur dioxide, ranging from injection into the soil as fertilizer to use in treatment of sewage, have also been proposed; and many of these have been discussed in a recent publication of the Sulphur Institute. However, removal of sulfur dioxide as a gas from industrial emissions would also present formidable technological problems.

There are other alternatives besides removal of sulfur from stack gases. Tall stacks to reduce local concentrations have already been mentioned; this procedure does not remove sulfur, it simply disperses it at greater distances. Another alternative is the use of low-sulfur fuel, but the supply of low-sulfur fuel in the world is limited. In this country most of the remaining low-sulfur coal is located in more remote areas such as the grasslands of eastern Montana. To bring this coal to industrial areas at a cost acceptable to industry would require strip mining, a process which has the potential of devastating the land and thus is quite unacceptable to residents of the affected areas and other people who do not want to see the land destroyed. Techniques for reclaiming strip-mined lands are under investigation, but there is some question as to whether they would be effective in moisture-deficient areas where the topsoil layer is very thin. A better approach might be a type of chemical coal mining, which essentially gasifies the coal underground.

Still another alternative is the desulfurization of fuel before it is burned. This, however, requires extensive pre-treatment of the fuel, such as the gasification of coal, and at the present time most research is directed toward the desulfurization of stack gases after the fuel is burned.

Strangely enough, the acid rain problem may be aggravated by some of the measures designed to reduce atmospheric pollution, such as reduction of particulate content of industrial emissions. A high percentage of particulate matter, especially that resulting from
combustion of fossil fuels, consists of alkaline metal oxides. In the past, this particulate matter may have served to neutralize some of the acid formed in the atmosphere. Reducing the particulates in the air may therefore actually aggravate the acid rain problem.

One of the automobile industry’s potential solutions to the automobile emission problem is the catalytic converter, designed to ensure complete combustion of hydrocarbons. It appears that a side effect of the converter is to transform trace amounts of sulfur in gasoline into sulfuric acid, which is then emitted as a sulfuric acid aerosol mist, another instance in which action taken to reduce one kind of pollutant may increase the production of another. The Environmental Protection Agency is now having second thoughts about forcing the use of the catalytic converter.

**CONCLUSION**

There are people who argue that sulfur pollution in the atmosphere is perhaps not entirely a bad situation. Sulfur in the atmosphere is not a phenomenon that originated with man. There is a natural sulfur cycle, and considerable amounts of sulfur in the atmosphere result from sea spray, biogenic emissions, and volcanic fumes. Furthermore, sulfur is a necessary plant nutrient, and the supply of sulfur in the soil is replenished by deposition from the atmosphere. Since many soils in the world are sulfur deficient, some people feel that sulfur pollution could act to remedy this deficiency. It has even been noted that acid rain has, under some circumstances, been shown to increase plant productivity. Indeed, work at the University of Arizona has demonstrated that there are soils in which application of sulfuric acid releases nutrients for utilization by plants. But even though sulfur in the atmosphere probably can act as a fertilizer when concentrations are low, higher concentrations which result in large-scale changes in ecosystems or serious alterations in the physiological processes of plants or animals must be avoided. A world already short of food and forest products can ill afford the risk (and the sheer economic waste) of possible decreased productivity of these critical resources.

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**Footnotes**

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1 Likens & Bormann, *Acid Rain: A Serious Regional Environ*
mental Problem, SCIENCE, 184:1176-79 (1974) [hereinafter cited as Likens & Bormann].

2 Id.


6 Likens & Bormann, supra note 1.

7 AIR POLLUTION ACROSS NATIONAL BOUNDARIES, supra note 5, at 35-43.

8 Lewis, Amdur, Fritzhand & Campbell, TOXICOLOGY OF ATMOSPHERIC SULFUR DIOXIDE DECAY PRODUCTS, Report No. AP-111, U.S. Environmental Protection Agency (1972) [hereinafter cited as Lewis].

9 Id.

10 National Air Pollution Control Administration, AIR QUALITY CRITERIA FOR SULPHUR OXIDES, Doc. # AP-50, at 71-102 (1969).


12 AIR POLLUTION ACROSS NATIONAL BOUNDARIES, supra note 5, at 32.


16 AIR POLLUTION ACROSS NATIONAL BOUNDARIES, supra note 5, at 54.
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17 Almer, supra note 14.
19 Oden, supra note 14, at 24.
22 Oden, supra note 14, at 32-34; Almer, supra note 14; Beamish, Loss of Fish Populations from Unexploited Remote Lakes in Ontario, Canada as a Consequence of Atmospheric Fallout of Acid, WATER RESEARCH, 8:89-95 (1974).
23 Oden, supra note 14, at 32-34.
24 Almer, supra note 14.
25 Id.
26 Id.
27 AIR POLLUTION ACROSS NATIONAL BOUNDARIES, supra note 5, at 57.
28 Oden, supra note 14, at 32.
29 Id. at 31; J.B. Cohen & A.G. Ruston, SMOKE: A STUDY OF TOWN AIR 55-59 (Edward Arnold and Company: London, 1925) [hereinafter cited as Cohen & Ruston].
30 AIR POLLUTION ACROSS NATIONAL BOUNDARIES, supra note 5, at 50; Liken & Bormann, supra note 1.
33 Oden, supra note 14, at 28.
34 Grennard & Ross, supra note 18.
36 Likens & Bormann, supra note 1.
37 Id.
39 R.W. Ferenbaugh, EFFECTS OF SIMULATED ACID RAIN ON
40 Id., at 47-48, 76-77.
42 Cohen & Ruston, supra note 29, at 53-55.
46 Engdahl, supra note 13, at 368.
47 Air Pollution Across National Boundaries, supra note 5, at 90.
49 Grennard & Ross, supra note 18.
53 Likens & Bormann, supra note 1.
57 Grennard & Ross, supra note 18; Kamprath, Possible Benefits from Sulfur in the Atmosphere, COMBUSTION. 44:16-17 (1972).
58 Grennard & Ross, supra note 18.