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REDUCING ACID RAIN IN EASTERN NORTH AMERICA: THE SCIENTIFIC BASIS FOR AN ACID RAIN CONTROL POLICY†

Michael Oppenheimer*

Annual rainfall in the eastern United States (EUS) is ten to forty times more acidic than normal. This acidity is due almost entirely to industrial and mobile source emissions of oxides of sulfur and nitrogen. Natural sources contribute only a small amount of sulfur and nitrogen to the atmosphere. In the EUS, these natural sources are generally estimated at less than five percent of the total. Sulfur dioxide emissions in the thirty-one-state EUS amounted to 22.5 million tons in 1980 of which sixteen million tons, or seventy-one percent, came from electric power plants, mostly coal-fired. Nitrogen oxide emissions amounted to fourteen million tons, of which mobile sources contributed more than forty percent and electric utilities about thirty percent.†

† This Article is adapted from the Environmental Defense Fund publication, M. OPPENHEIMER, REDUCING ACID RAIN: THE SCIENTIFIC BASIS FOR AN ACID RAIN CONTROL POLICY (1984).
1. As used in this Article, the “eastern United States” (EUS) is defined as the 26 states east of the Mississippi River and the five states contiguous to it on the west. The western United States is also beginning to suffer from acid rain damage, but I do not discuss that problem in this Article because the sources of the damage are different from those in the East. For a summary of this problem, see the Environmental Defense Fund publication, R. YUHNKE & M. OPPENHEIMER, SAFEGUARDING ACID-SENSITIVE WATERS IN THE INTERMOUNTAIN WEST (1984).
3. Most of these oxides are derived from “anthropogenic” sources, either fuel combustion (e.g., power plants and internal combustion engines) or reduction processes (e.g., smelters). U.S. ENVTL. PROTECTION AGENCY, U.S.-CANADA MEMORANDUM OF INTENT ON TRANSBOUNDARY AIR POLLUTION, PHASE II INTERIM REPORT (1981) [hereinafter cited as U.S.-CANADA M.O.I., PHASE II INTERIM REPORT]; Galloway & Whelpdale, An Atmospheric Sulfur Budget for Eastern North America, 14 ATMOSPHERIC ENV'T 409 (1980). They are first emitted as sulfur dioxide and various oxides of nitrogen. Subsequently, these pollutants are eliminated from the atmosphere by several pathways. See infra Part II.
5. U.S. ENVTL. PROTECTION AGENCY, U.S.-CANADA MEMORANDUM OF INTENT ON TRANSBOUNDARY AIR POLLUTION, REPORT OF WORKING GROUP 1 (1983) [hereinafter cited as U.S.-
Acid rain is part of a more general phenomenon called acid deposition. Sulfur and nitrogen may fall to earth as the original sulfur dioxide and nitrogen oxides or may be converted to acids by chemical reactions in the atmosphere. These acids may fall to earth in precipitation, commonly known as "acid rain," or as acid droplets and gases during dry periods.\textsuperscript{6} Almost all sulfur and nitrogen oxides that fall on land in any of these forms become acid in our watersheds, forests, and soils.\textsuperscript{7} Therefore, total deposition, wet and dry, is the best measure of ecosystem impacts. Because each sulfur molecule contributes twice as much acid as each nitrogen molecule,\textsuperscript{8} two-thirds to three-quarters of the total acid falling on land originates in sulfur emissions.

Due to shifts in fuel consumption patterns, sulfur emissions and measured sulfur deposition have decreased slowly in the Northeast over the last two decades, but have increased in the southern and border states. Some midwestern states have shown increases and others decreases. Nitrogen emissions and deposition have generally increased. Sulfur deposition remains well above levels that are considered "safe" for aquatic systems\textsuperscript{9} even in states with emissions decreases.

The effects of these acids on our environment have been amply documented. As shown in table I, surface waters in about a dozen areas of eastern North America have been chronically acidified,\textsuperscript{10} with evidence of large alterations over the last three or four decades.\textsuperscript{11} The effects related to watershed acidification include (1) the leaching of toxic metals into surface waters and

\textsuperscript{6} Sulfur dioxide and nitrogen oxides react chemically in the gas phase to produce aerosols and gaseous acids. Sulfur dioxide and nitrogen oxides may be incorporated into clouds, transformed to sulfuric and nitric acid and various other nitrates and sulfates, and rained or snowed out in precipitation. Aerosols and gaseous acids may also be rained or snowed out. This process is called "wet deposition." Sulfur dioxide and nitrogen oxides, as well as aerosol sulfates and nitrates and gaseous nitric acid, may settle on surfaces directly in a process called "dry deposition." \textit{See generally NATIONAL RESEARCH COUNCIL, ACID DEPOSITION: ATMOSPHERIC PROCESSES IN EASTERN NORTH AMERICA} 29-54, 155-201, 213-373 (1983); Hales, \textit{Wet Removal of Sulfur Compounds from the Atmosphere}, 12 \textit{ATMOSPHERIC ENV'T} 389 (1978); Oppenheimer, \textit{The Relationship of Sulfur Emissions to Sulfate in Precipitation} (pt. 1), 17 \textit{ATMOSPHERIC ENV'T} 451 (1983).

\textsuperscript{7} U.S.E.P.A., \textit{ACIDIC DEPOSITION PHENOMENON}, \textit{supra} note 2.

\textsuperscript{8} Id.

\textsuperscript{9} \textit{See infra} Part II.

\textsuperscript{10} For the purposes of this Article, I define "chronically acidified" as the absence of bicarbonate alkalinity or buffering capacity on an annual average basis, with pH values generally below 5.3. \textit{See infra} note 12.

\textsuperscript{11} U.S.-CANADA M.O.I., \textit{WORKING GROUP} 1, \textit{supra} note 5.
TABLE I

Some Studies of Acidified Waters in the Eastern United States

<table>
<thead>
<tr>
<th>Location</th>
<th>Recent Wet Sulfate Deposition Maximum Value, kg/hectare/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adirondack Mountains,</td>
<td>40</td>
</tr>
<tr>
<td>New Yorkb</td>
<td></td>
</tr>
<tr>
<td>New Jerseyc</td>
<td>35</td>
</tr>
<tr>
<td>Northern Wisconsind</td>
<td>13-16</td>
</tr>
<tr>
<td>Upper Peninsula, Michigan</td>
<td>18</td>
</tr>
<tr>
<td>New Englandf</td>
<td>35</td>
</tr>
</tbody>
</table>

a. For additional locations and references, see U.S.E.P.A., ACIDIC DEPOSITION PHENOMENON, supra note 2.
perhaps groundwaters, including drinking water supplies; (2) the
destruction of a wide variety of fish populations as well as other
aquatic plants and animals due to the combined effects of acid
and toxic metals; (3) the leaching of nutrients from soils and
their removal from the watershed; (4) the possible destruction of
fungi and bacteria that figure in nutrient and transpiration cy-
cles; and (5) the probable stress on forests yielding excess mor-
tality and reduced rates of growth of trees and other species.
Effects not related to watersheds include (1) reductions in some
crop yields; (2) the accelerated corrosion of structural materials;
and (3) the probable aggravation of human respiratory and car-
diovascular problems due to enhanced concentrations of air-
borne acidic pollutants and precursors.

Watershed effects related to surface water acidification have
been intensively studied, and thus provide a quantitative basis
for control strategies. Among the patterns now emerging is a de-
crease in pH and alkalinities in, and therefore the acid neutraliz-
ing capacity of, acid-sensitive surface waters at many locations
in the East over the last three decades. Organic soil acids are
ruled out as a significant source of these regional acidification
changes in clearwater lakes and streams. Among the reasons
for this conclusion are that acidified clear surface waters, as dis-
tinguished from natural, colored acid bogs, exist only in areas
receiving intense acid deposition with pH less than 4.7 and are
dominated by sulfuric and nitric, rather than organic, acids.
Acid deposition into clear surface waters is chemically altering
thousands of lakes and stream miles, although many fall short of
a total loss of alkalinity and chronic acidification.

Reducing acid deposition and preventing further deterioration
of human health and the environment in the EUS due to acidifi-
cation present regulators with highly complex problems made
more difficult by the inadequacies of existing regulatory authori-
ties. A likely starting point for an effective acid rain control

12. A watershed's acid neutralizing capacity refers to the collection of chemical
processes that counteract acid in soils and waters. Alkalinity, which generally measures
bicarbonate in water, is one measure of this capacity. See generally National Research
Council, supra note 6, at 12-16, 26 n.2.

13. U.S.E.P.A., ACIDIC DEPOSITION PHENOMENON, supra note 2; G. Hendrey, N. Camus
& E. Balzer, Jr., Transport, Fate and Effects of Energy-Related Pollutants: Evaluation of
Surface and Groundwaters (1982) (report for Brookhaven National Laboratory, Upton,
N.Y., copy on file with Environmental Defense Fund).

14. U.S.E.P.A., ACIDIC DEPOSITION PHENOMENON, supra note 2; U.S. ENVTL. PROTEC-
TION AGENCY, U.S.-CANADA MEMORANDUM OF INTENT ON TRANSBOUNDARY AIR POLLUTION,
REPORT OF WORKING GROUP 3B (1983) [hereinafter cited as U.S.-CANADA M.O.I., WORKING
GROUP 3B]; G. Hendrey, N. Camus & E. Balzer, Jr., supra note 13.
Reducing Acid Rain

strategy is the Clean Air Act (the Act),\textsuperscript{15} which offers a variety of control options for regulating the emission of air pollutants.\textsuperscript{16} Although more aggressive implementation of present Clean Air Act provisions could provide significant reductions in sulfur di-

\textsuperscript{15} 42 U.S.C. §§ 7401-7642 (1982).

\textsuperscript{16} The Clean Air Act establishes a national regulatory framework for controlling air pollution. \textit{Id.} § 7407. The Act is administered by the U.S. Environmental Protection Agency (EPA). \textit{Id.} § 7601. Nationally uniform ambient air quality standards (NAAQS), promulgated by EPA for pollutants that adversely affect health and welfare, guide implementation. \textit{Id.} §§ 7408-7409. States are required to devise implementation plans to limit emissions from existing stationary sources and motor vehicles in use within each air quality control region to ensure attainment of federal standards. \textit{Id.} § 7410.

The Act further provides for three sets of nationally uniform federal emission limitations, including those for new stationary sources. \textit{Id.} § 7411. New source performance standards (NSPS) require the best level of emission reduction achievable that, taking into account costs, energy use requirements, and health and welfare effects, EPA determines "has been adequately demonstrated." \textit{Id.} § 7411(a)(1); \textit{see also id.} § 7412 (nationally uniform federal emission limitations for "hazardous air pollutants"); \textit{id.} § 7521 (nationally uniform federal emission limitations for new motor vehicles).

Related to NSPS are programs that (1) prevent significant deterioration (PSD) of areas currently attaining federal ambient standards, and (2) accommodate industrial growth while continuing progress toward attainment of NAAQS in areas not currently meeting NAAQS, or "nonattainment areas." The PSD program requires preconstruction review of all major new sources in attainment areas and requires such sources to use the "best available control technology" (BACT), an emission limitation based on the maximum degree of reduction of each regulated pollutant, taking into account energy, environmental, and other economic costs, \textit{id.} § 7479(3), to ensure that emissions will not cause a violation of permissible increments in ambient air pollution in specified PSD regions. \textit{See id.} §§ 7470-7479.

In nonattainment areas, major new sources must use control technology to meet the "lowest achievable emission rate" (LAER), the most stringent emission limitation contained in any state implementation plan (SIP) or the lowest emission rate achieved by any similar source in the country. \textit{Id.} §§ 7501(3), 7503(2). In addition, major new sources are allowed in nonattainment areas only if their emissions are more than offset by reductions from existing sources in the region. \textit{Id.} § 7503(1)(A). Existing sources must apply "reasonably available control technology" (RACT), or that technology which is reasonably available considering technological and current feasibility. \textit{Id.} § 7502(b)(3). Through these measures, states must provide for attainment of NAAQS "as expeditiously as practicable." \textit{Id.} § 7502(a)(1).

The Act seeks to control interstate pollution by requiring SIPs to prohibit emissions from stationary sources that will "prevent attainment or maintenance" of ambient standards by other states or will "interfere with" measures required to prevent significant deterioration or protect visibility in other states. \textit{Id.} § 7410(a)(2)(E); \textit{see also id.} §§ 7475(a)(3), 7491(b)(2) (major new sources may not lead to violations of ambient standards, permissible PSD increments, or visibility requirements in other air quality control regions). The Act also provides EPA with authority to require SIP revisions in order to prevent international pollution that endangers "public health or welfare in a foreign country." \textit{Id.} § 7415.

oxide and nitrogen oxides emissions,\textsuperscript{17} regulating emissions on

\begin{quote}
17. One commentator has suggested that "shortsighted, overly-cautious administrative interpretation," and not the basic structure of the Act, is at the heart of a currently inadequate acid rain policy. Edwards, \textit{Through the Crevices: Acid Rain and the Clean Air Act}, 11 \textit{Ohio N.U.L. Rev.} 671, 673 (1984); see also Wooley & Wappett, \textit{Cumulative Impacts and the Clean Air Act: An Acid Rain Strategy}, 47 \textit{Alb. L. Rev.} 37, 43-50 (1982) (The Act could be utilized effectively to control cumulative effects of acid rain, but current EPA policy prevents fulfillment of the Act's objectives.). Professor Edwards argues that existing provisions can be "adapted" to provide an effective administrative response, at least until "meaningful legislative action" is taken. Edwards, supra, at 673. He recommends numerous actions under the present Act, including the promulgation of stricter NAAQS for sulfur dioxide and nitrogen oxides, more aggressive federal enforcement based upon models of direct interregional impacts of individual sources, imposing stricter BACT in attainment areas, and restricting the trading and banking of offsets of sulfur dioxide and nitrogen oxides emissions in nonattainment areas. \textit{Id.} at 684-723.

The Act provides EPA with several other options for controlling acid deposition. Under § 109, EPA is required to prescribe secondary NAAQS "requisite to protect the public welfare from any known or anticipated adverse effects associated with the presence of [air pollutants for which air quality criteria have been issued]." 42 U.S.C. § 7409(b)(2) (1982); see id. § 7408(a) (air quality criteria for specific pollutants must indicate, \textit{inter alia}, effects on "public health or welfare" and "any known or anticipated adverse effects on welfare"). The Act defines "public welfare" as including "effects on soils, waters, crops, vegetation, manmade materials, animals, wildlife, weather, visibility, and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being." \textit{Id.} § 7602(h). The Environmental Defense Fund has sued to force EPA to set air quality standards for acid deposition precursors reflective of the health and welfare effects of acid deposition in the EUS. \textit{Environmental Defense Fund v. Thomas}, No. 85 Civ. 9507 (S.D.N.Y. filed Dec. 5, 1985).

Section 115 of the Act provides that whenever EPA "has reason to believe that any air pollutant or pollutants emitted in the United States cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare in a foreign country," the Agency must notify the states from which the harmful emissions originate. 42 U.S.C. § 7415(a) (1982). This notice constitutes a finding by EPA that the SIPs of those states are "substantially inadequate to . . . comply with [the Act]." \textit{Id.} §§ 7415(b), 7410(a)(2)(H)(ii). Upon such a finding, states are required to revise their SIPs to prevent or eliminate the endangerment of public health or welfare in the foreign country. \textit{Id.} Section 115 findings may be made only as to foreign countries that EPA determines have "given the United States essentially the same rights with respect to the prevention or control of air pollution occurring in that country as is given that country by this section." \textit{Id.} § 7415(c). In \textit{New York v. Ruckleshaus}, 613 F. Supp. 1472 (D.D.C. 1985), appeal docketed sub nom. \textit{New York v. Thomas}, No. 85-5970 (D.C. Cir. filed Sept. 26, 1985), the court held that two letters sent in 1981 by then-EPA Administrator Douglas Costle to then-Secretary of State Edmund Muskie and Sen. George Mitchell constituted § 115 endangerment and reciprocity findings with respect to acid deposition and gave rise to a nondiscretionary duty on EPA's part to notify states with harmful emissions and "to set in motion the necessary processes to require a plan revision so as to prevent or eliminate the endangerment encompassed by the Costle determinations." 613 F. Supp. at 1486.

Eight northeastern states have challenged EPA's denial of a number of state petitions under § 126(b), \textit{Id.} § 7426(b), for findings that air pollution from midwestern states causes acid deposition in northeastern states and prevents their attainment of sulfur dioxide NAAQS, consumes portions of their PSD increments, and interferes with visibility. \textit{New York v. EPA}, No. 84-1592 (D.C. Cir. filed Dec. 6, 1984). Such a finding would require emissions reductions by major sources in the midwestern states. 42 U.S.C. §
the basis of nationally uniform health-based ambient standards cannot adequately protect ecosystems from acid deposition.\textsuperscript{18} Achieving sufficient reductions in acid deposition to protect against the risks to health and the environment in the northeastern United States and southeastern Canada will require substantial overall reductions in sulfur dioxide emissions in the thirty-one-state EUS. Reductions on this scale, although theoretically achievable through regulatory actions under its “welfare” provisions,\textsuperscript{19} may not be politically realistic under the present Act. Additional statutory authority is needed to deal specifically with the acid rain problem.

This Article presents the scientific basis for an effective acid rain control policy. Part I suggests that if a choice must be made, regulation should focus primarily on sulfur dioxide emissions rather than nitrogen oxide emissions because sulfur deposition is the major cause of watershed acidification. Part II explains the need for at least a fifty percent reduction in sulfur dioxide emissions to meet a “safe” deposition level. Part III specifies the geographical allocation of sulfur emission reduc-


\textsuperscript{19} See 42 U.S.C. §§ 7408(a), 7409(b)(2), 7602(h) (1982); supra note 17.
tions necessary to attain target deposition levels in the north-eastern United States and southeastern Canada. The Article concludes by demonstrating the need for swift adoption and implementation of an effective acid deposition control strategy in light of large future risks of accumulating irreversible damage.

I. SULFUR EMISSIONS AS THE PRIMARY OBJECT OF CONTROL

Because sulfur deposition is responsible for two-thirds to three-quarters of the acid entering our ecosystem, it is an obvious primary choice for control. Furthermore, on an annual average basis, sulfur is almost entirely responsible for increased acidity and decreased alkalinity in eastern surface waters because most nitrogen added to watersheds is taken up in biological activity as a fertilizer, with the accompanying removal of its associated acid.20

The different response of watersheds to sulfur and nitrogen is illustrated in figure 1, which compares the sulfur and nitrogen input to watersheds through wet deposition from the atmosphere with the output from the watersheds' lakes. This figure is drawn from a watershed data base characteristic of the north-eastern United States and southeastern Canada. A small amount—ten to fifty percent—of nitrogen leaves a watershed compared to the amount that enters in wet deposition. When the dry deposition input is also taken into account, it is obvious that only a small fraction of nitrogen entering watersheds actually ends up in lakewater. In contrast, more sulfur generally leaves waters than enters as wet deposition, with the discrepancy largely accounted for by dry deposition.21 Thus, biological processes at work in watersheds can absorb nitrogen compounds and prevent them from affecting lakewater chemistry, but the same processes do not affect sulfur compounds, which pass directly into the water bodies. For watersheds in the Southeast, the soils tend to absorb sulfur, so that only about half the atmospherically deposited sulfur enters the waterbodies.22

21. Id.
22. Johnson, Hornbeck, Kelly, Swank & Todd, Regional Patterns of Soil Sulfate Accumulation: Relevance to Ecosystem Sulfur Budgets, in Atmospheric Sulfur Deposition 507 (1980). Recent reports indicate that microbiological processes do remove sulfur in limited amounts from the waters of some northern lakes, but the general picture presented above remains unchanged.
Output of sulfur and nitrogen from watersheds plotted vs. input due to wet deposition. Solid line indicates output = input.

case, sulfur far outweighs nitrogen in its contribution to long-term acidification.

In spite of its relative unimportance in chronic acidification, nitric acid in lake water can sometimes increase markedly during spring snowmelt because biological uptake is minimal, melt water is not easily neutralized by contact with the frozen ground, and nitrogen concentrations may be relatively high compared to sulfur in snowpack.23 At some locations in the Northeast, and in high mountain areas of the West, such episodic acidification may continue to occur even if sulfur deposition is reduced. Although the long-term biological significance of these episodes is unclear in eastern North America,24 reducing sulfur deposition will ameliorate episodic acidification to some degree in any watershed because sulfur augments the effect of nitric acid shock.25 Finally, the increase of nitrate in lakewater in the spring snowmelt observed in some Adirondack and New England watersheds may not be typical of much of eastern North America.26

Another factor that must be weighed in determining the relative importance of sulfur and nitrogen in ecosystem acidification is the role of atmospheric oxidants in determining sulfur deposition rates. Oxidants must be present to convert emitted sulfur dioxide into deposited sulfuric acid, so the concentration of oxidants in the atmosphere will determine whether reductions in sulfur emissions lead to proportional reductions in sulfur deposition. This is the so-called linearity issue: whether a one-to-one relation exists between sulfur emissions reductions and reduction of downwind acid rain.27 The oxidant level is tied to the concentration of nitrogen oxides and hydrocarbons, the major

23. This is an example of "episodic" acidification. Generally speaking, episodic acidification occurs for a few days after a heavy acid rain and for several weeks after springtime snowmelts.

24. Excess amounts of nitric acid introduced into a watershed through episodic acidification may so upset the chemical balance of lakes and streams as to cause biological "shock" to fish. Large springtime fish kills on the scale of those reported in Europe have not occurred in North America.


27. For a full discussion of the linearity issue, see NATIONAL RESEARCH COUNCIL, supra note 6, at 72-82.
precursors of smog. A 1983 National Research Council (NRC) report\(^{28}\) and my own scientific research\(^{29}\) indicate that oxidants are available in sufficient quantities to permit, on an annual average basis, a linear transformation of sulfur dioxide to acid rain.

Generally, reductions in emissions of sulfur dioxide from any source will yield proportional reductions in the sulfur deposited in the northeastern United States from that source. If all significant sources were reduced by half, sulfur deposition at almost all receptors would be reduced by half. Furthermore, if emissions of ammonia, which can lower acidity, and nitrogen oxides do not change, a given sulfur dioxide reduction will yield at least as great a decrease in precipitation acidity. A fifty percent sulfur dioxide reduction will yield an increase of 0.3 or more in precipitation pH. Only decreases in sulfur dioxide emissions, and not decreases in the emissions of nitrogen oxides or hydrocarbons, will produce proportional decreases in total sulfur deposition, wet plus dry.

In summary, for watershed effects in the East involving surface waters, soils, and possibly trees, sulfur deposition is the major source of long-term problems associated with acidification, although the episodic effects related to nitrogen may have long-term biological significance at some locations. Therefore, the first priority for control of watershed acidification is control of sulfur deposition. The most effective means to control sulfur deposition is to reduce sulfur dioxide emissions. Such controls will also reduce non-watershed effects such as crop damage and tree-leaf damage, and will ameliorate corrosion of structural materials. Based on current knowledge, if a choice must be made, emissions reduction efforts should focus first on sulfur dioxide, then on nitrogen oxide emissions reductions. In the long term, however, both are necessary to protect fully the environment. Recent indications of nitrogen "poisoning" of forests due to nitrate overfertilizing from the atmosphere suggest that nitrate must be included in control strategies.

\(^{28}\) Id. at 7-9, 84, 139-40.

II. The Required Amounts of Sulfur Dioxide Emissions Reductions

Aquatic effects of acid rain have received the most careful quantitative study and, as noted above, these studies provide a quantitative basis for emissions control. It is generally understood that the addition of sulfuric acid to a watershed is counteracted by three processes: absorption of sulfur by soils; exchange and transfer of hydrogen ions and various cations in soils; and titration, the neutralization of hydrogen ions by weathered alkalinity. After a sufficient time, however, the capacity of soils to absorb sulfur and exchange cations is reduced. Furthermore, the ability of the soil to furnish alkaline, bicarbonate material to the water flow may be exceeded by the amount of acid deposited into the watershed. Once the acid input exceeds the output of alkalinity, the pH of waterbodies will fall with small increases in acid input, and waters become acidified.

The exact deposition rate at which waters acidify depends on the remaining absorption and exchange capacity of a watershed, as well as the output of alkalinity. From observations at several locations in North America, however, it appears that chronic acidification has not occurred where wet sulfate deposition remains below thirteen to sixteen kg/hectare/year. For almost all sensitive areas of eastern North America, wet deposition in 1980 was below forty kg/hectare. Thus, a deposition reduction that exceeds sixty percent at some locations would protect all sensitive waters from acidification by partially reversing chemical change in some watersheds and slowing it in others. Reductions that do not reach the target deposition level would leave some waters unprotected.

Parts of all thirty-one eastern states currently receive thirteen to sixteen kg/hectare/year or more of wet sulfate deposition, suggesting the need for a thirty-one-state control program. This target should be regarded with caution because regional-scale acid deposition has been occurring for only thirty to forty years in eastern North America. Cumulative acidification due to reduced neutralization capacity may occur at lower sulfur deposition levels over a longer time. Achieving the target deposition level,

30. See supra table I; U.S.-Canada M.O.I., Working Group 3b, supra note 14. In U.S. equivalents, one hectare equals approximately 2.5 acres; a kilogram (kg) equals approximately 2.2 pounds. Thus, the suggested "safe" annual wet sulfate deposition level may be redefined as approximately 11.4 to 14.0 pounds per acre.

31. See infra notes 48-58 and accompanying text.
however, will prevent acidification under current conditions and will slow the rate of change of watershed chemistry.

The effectiveness of this target can be expected to extend beyond surface water protection. To the extent that soil-water flow is prevented from acidifying, nutrient leaching and toxic metal mobilization are decreased, creating a healthier environment for trees and other species. The target deposition level can be attained with a regional average emissions reduction of about fifty percent if larger-than-average reductions are targeted on large-emission regions, because these regions also correspond to the deposition maximums.

III. THE GEOGRAPHICAL ALLOCATION OF SULFUR EMISSIONS REDUCTIONS

Several principles can guide the choice of emissions reductions allocations among the states. First, emissions reductions should be allocated so that all eastern sensitive areas can achieve the target deposition level of below thirteen to sixteen kg/hectare/year. Second, strategies that focus reductions on large emitters can achieve target deposition levels with a lower average reduction. Third, although detailed source-receptor relationships are not precisely known, and the quantitative value of current atmospheric models is somewhat limited, several lines of evidence suggest that distant sources are a major contributor to acid deposition at most receptors of interest. Strong evidence of this phenomenon is contained in the 1983 NRC analysis, indicating that the atmosphere is generally well-mixed in the region from Tennessee and Illinois northeast over distances of 1000 kilometers. Furthermore, the NRC report concluded that most of the acid rain falling at three locations analyzed in New York and Canada originated at sources lying in the direction of the Midwest. The study also showed that strong local sources, such as the Sudbury smelter, do not dominate local acid rain within

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32. See supra notes 6 & 27.
33. National Research Council, supra note 6, at 128-29. Although the mixing is not perfect, particularly near the edges of the region, one expects the largest sources to make the largest contributions to deposition at most remote receptors. Large source states beyond 1000 kilometers from receptors still make a significant, although less than proportional, contribution to deposition. Therefore, a given percentage reduction in sulfur dioxide emissions within any such 1000-kilometer region will tend to produce the largest deposition reductions at most remote receptors if focused on the largest sources.
34. Id. at 140-41.
35. Located in Ontario, Canada, the Sudbury smelter is sometimes responsible for up to five percent of all sulfur dioxide emissions in eastern North America.
even a few tens of kilometers of the source. Finally, all long-range transport models support the notion that distant sources are major contributors to deposition.

These three principles lead to the conclusion that all Ohio Basin-Midwest coal burning states should be included in a control program. This region is a hub about which all sensitive areas in the thirty-one-state EUS region are located. Most sensitive areas are inside or within 1000 kilometers of some coal burning states. Figure 2 demonstrates that 1000-kilometer circles around each sensitive area yield a set of mixing zones that cover the entire thirty-one-state region and that overlap in the Midwest. Therefore, emissions reductions in the Midwest should strongly affect all sensitive areas. In contrast, emissions reductions in New York and New England, for example, have little effect outside New York and New England.

The importance of the Ohio Basin to a regional program is underscored by emissions inventories. The nine largest coal burning states emit nearly two-thirds of eastern sulfur dioxide while the seven New York-New England (NY-NE) states emit six percent of eastern sulfur dioxide. Furthermore, available analyses demonstrate that target deposition levels cannot be attained in the NY-NE states by tapping those states' sources alone, simply because not enough sulfur is emitted in the region. Even shutting off entirely all sulfur sources of the NY-NE states will not meet target levels in those states. Therefore, target deposition levels cannot be achieved generally unless Ohio Basin states participate in a reduction program.

For a variety of reasons including cost, several proposed acid deposition control programs deviate from a uniform percent reduction by focusing the largest reductions in the Ohio Basin.

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36. NATIONAL RESEARCH COUNCIL, supra note 6, at 140.
37. Id. at 140-41. According to several current models, sources outside the New York-New England (NY-NE) states contribute 75% or more of the sulfur deposition in the Adirondacks. See, e.g., OFFICE OF TECHNOLOGY ASSESSMENT, 98TH CONG., 2D SESS., ACID RAIN AND TRANSPORTED AIR POLLUTANTS: IMPLICATIONS FOR PUBLIC POLICY, O.T.A. REP. No. OTA-0-204, at 73-74, 279-85 (1984).
38. See S. REP. No. 426, supra note 18, at 51-53.
40. The principal bills to reduce acid deposition in past sessions of Congress would have required Ohio Basin states to shoulder most of the specified emissions reductions. A Senate bill, reported out of the Senate Environment and Public Works Committee in 1984, see S. REP. No. 426, supra note 18, would have established an "acid deposition impact region" consisting of the EUS. S. 768, 98th Cong., 1st Sess. § 181, 129 CONG. REC. S2583 (daily ed. Mar. 10, 1983). The bill would have required a 50% reduction of sulfur
FIGURE 2

1000 km radii about four sensitive areas
Because of long-range atmospheric mixing, target deposition levels probably can be achieved at all sensitive receptors with the largest percentage reductions in the Midwest and other large-emitter states, and lower percentage reductions in small-emitter states more local to those receptors. For instance, an analysis performed for the congressional Office of Technology Assessment (OTA) indicates that an overall fifty percent reduction allocated proportionally to current emissions in excess of 1.2 pounds of sulfur dioxide per million Btu can provide a forty to sixty-five percent deposition reduction at all receptors with the larger reduction occurring where the largest deposition now occurs. The lower reductions occur at receptors currently receiving considerably less than forty kg/hectare/year due to their remote locations. Target levels in most areas cannot be achieved if midwestern states are not included in the program. Eliminating any large-emission states from the program will necessitate even higher reductions in the remaining states.

In summary, a thirty-one-state overall fifty percent sulfur dioxide emissions reduction program with the highest reductions in the large-emission states including the Midwest can probably achieve target deposition levels in all eastern sensitive areas. The reduction in emissions in large-emitter states will reduce pollution damage to crops, materials, and human health, and improve visibility in those states even in the absence of sensitive areas. A program that centers on the NY-NE states will not benefit sensitive areas in the Southeast, the Great Smokies, or the upper Midwest.

dioxide emission levels with Ohio Basin states bearing the largest quantitative reductions. Id. § 184; see S. Rep. No. 426, supra note 18, at 61-62.

A House bill introduced in 1983 would have spread the cost of sulfur dioxide emissions reductions among the 48 continental states but required the 50 largest-emitting power plants to install scrubbers to provide 70% of the reductions. H.R. 3400, 98th Cong., 1st Sess. §§ 185-186, 129 Cong. Rec. H4473 (daily ed. June 23, 1983) [hereinafter cited as H.R. 3400]. Because the 50 largest uncontrolled sulfur dioxide emitters are located in the EUS, S. Rep. No. 426, supra note 18, at 53, and because the other 30% of the reductions would be allocated according to average power plant emissions, H.R. 3400, supra, § 191, this proposal also contemplated the largest emissions reductions coming from the Ohio Basin states.


41. OFFICE OF TECHNOLOGY ASSESSMENT, supra note 37.
IV. THE APPROPRIATE TIME SCALE FOR EMISSIONS REDUCTIONS

A critical issue of an effective acid rain control policy is the appropriate schedule for reducing sulfur dioxide emissions. Two separate questions must be addressed. First, what trend, if any, can be projected for emissions in the absence of additional emissions controls? Second, what chemical and biological changes in the ecosystem can be anticipated in the absence of deposition reductions?

With respect to the first question, it has been argued that turnover will result in the replacement of retiring uncontrolled power plants with new plants with seventy to ninety percent sulfur removal, as required under current law. As a result, utility sulfur dioxide emissions may decline significantly below current levels by the first part of the next century.

Putting aside the question of the desirability of waiting several decades to achieve that level of emissions, let us examine the assumptions in the argument. OTA has projected utility sulfur dioxide emissions under a variety of assumptions on electricity use, or load growth, and retirement schedules for currently existing power plants. Using an average power plant retirement age of forty years and a load growth rate of 2.5% per year, utility emissions are cut in half by the year 2015. This reduction would reduce total emissions from all source sectors by only twenty to twenty-five percent, depending on projected growth in the industrial sector. In any event, target deposition levels are not generally achieved without additional reductions.

Both the rate of increase assumed for fossil fuel-generated electricity demand and the retirement age of plants are highly uncertain, however, with the former probably overestimated and the latter probably underestimated. In particular, it is likely the utilities will make every effort to extend the lifetime of existing facilities, assuming that the current disincentives for major capital projects continue to exist. To make predictions, OTA has

43. OFFICE OF TECHNOLOGY ASSESSMENT, supra note 37, at 61-62.
44. Id.
45. Id. at 59-60.
46. See Lihach, Extending the Lifespan of Fossil Plants, 8 ELECTRIC POWER RESEARCH INST. J., June 1983, at 6. A further disincentive for the retirement of existing power plants is the stringency of NSPS for new coal-fired power plants. See supra note 42 and accompanying text; Edwards, supra note 17, at 705 & n.155.
analyzed several scenarios of growth and retirement age. If the retirement age is extended to sixty years, utility emissions in 2025 would still be ninety to one hundred percent of current levels if fossil fuel-based demand grows at only one to two percent per year. Given the uncertainties in retirement age and load growth, the existing Clean Air Act hardly can be counted on to reduce adequately acid deposition.47

Finally, we arrive at the issue of time scales for chemical and biological change in the ecosystem. Acid deposition already has altered parts of our ecosystem both chemically and biologically. Some of the damage is cumulative in that constant acid deposition at current levels adds to chemical and biological change. Materials corrosion damage, for instance, is in this category.

Other damage may or may not be cumulative. Watersheds arguably may be in a "steady-state" at constant levels of deposition, and, if emissions remain constant, cumulative damage will not occur.48 This is a "what you see is what you get" theory. A thorough census of resources would indicate all extant damage. Thus, emissions reductions may reverse some of those damages but waiting would entail no new damages.

On the other hand, the parts of the ecosystem that are not in a "steady-state" are changing chemically and biologically, sometimes in an irreversible fashion. To understand how, consider a typical forested watershed. Sulfuric acid in rain interacts with that system in several ways. These interactions include (1) the retention of sulfur by soils; (2) the release of base cations, other metals, and alkalinity by exchange and transfer reactions with hydrogen ions; and (3) the neutralization of alkalinity after weathering.49 The first two of these processes are changing forest soils and watershed neutralizing capacity in a cumulative non-steady-state manner. Loss of readily weathered base cations increases in response to acid rain,50 but this neutralization capacity can be lost in several decades. The question is, how fast is it

47. Because most sulfur dioxide emissions originate from sources that were built before Clean Air Act standards became effective, they are not subject to NSPS and are subject only to minimal state emission limitations to achieve NAAQS. Edwards, supra note 17, at 705 & n.154; Syracuse Note, supra note 18, at 624-25. It is estimated that as late as the year 2000, 75% of sulfur dioxide emissions will still be coming from sources built before 1970. Lee, supra note 18, at 81.

48. See, e.g., NATIONAL RESEARCH COUNCIL, supra note 6, at 20-21.

49. See supra Part II.

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replenished? Some paleolimnological evidence implying decreasing lakewater pH at constant sulfur deposition suggests that the replenishment time may be measured in centuries rather than decades—much longer than the exhaustion time in many cases. If so, loss of readily weathered cations is effectively irreversible. Loss of calcium from soils at some locations over a few decades supports the notion of irreversible leaching. Thus, an assumption of a steady-state situation is unwarranted, as is the assumption that cations or neutralization capacity will not diminish for decades. The outcome of this process is a cumulative, effectively irreversible loss of watershed nutrients and neutralizing capacity that is significant compared to readily available stores. The likely end result of this process is the continuous addition of surface waters to the "acidified" category.

A second source of change due to constant acid deposition is the accumulation of sulfur in watershed soils. In areas outside the Northeast, soils retain the capability to absorb sulfur and its accompanying acid ions. In soils of the Northeast, this capacity no longer exists. At constant levels of acid deposition, the soils in the Southeast will absorb sulfur until reaching a certain limit. At that time, a steady-state is reached with input and output in balance. As this point is reached, however, output increases and the sulfur reaching watershed lakes and streams increases as do its accompanying acid ions. Therefore, the acid input to surface waters will continue to increase in southern lakes and streams.

Because the limiting point may be reached within several decades, and because half of all sulfur deposited is currently absorbed by soils, large increases in the number of acidified surface waters can be expected in the next few decades unless deposition is decreased. These systems are obviously not at steady-state at the current time.

Another source of change is biological accommodation to fixed aquatic and watershed chemistry. Even if these chemical systems are not changing now, their concomitant biota are changing to adjust to chemical conditions that may have become steady. For instance, the thousands of lakes with pH between 5.0 and


52. See Galloway, Norton & Church, Freshwater Acidification from Atmospheric Deposition of Sulfuric Acid: A Conceptual Model, 17 ENVTL. SCI. TECH. 541A (1983).

53. Johnson, Hornbeck, Kelly, Swank & Todd, supra note 22.

54. See FISH & WILDLIFE SERV., U.S. DEP'T OF THE INTERIOR, A REGIONAL SURVEY OF THE CHEMISTRY OF HEADWATER LAKES IN NEW ENGLAND: VULNERABILITY TO ACIDIFICATION
may not change much chemically if acid deposition has stabilized, but their biota, such as fish populations, may take years to adjust. An example is lakes that currently have only large and old fish in them. The entire population will eventually disappear due to lack of recruitment. Another example is the radical change in flora atop Camels Hump Mountain in Vermont within only twenty years, at constant deposition levels. Such biological adjustments will feed back on the aquatic chemistry.

Finally, apparently stable biological systems can suddenly change in an irreversible manner due to other stresses. An example is the recent decline in the Black Forest in West Germany in only two or three years, at relatively constant pollutant levels. It is speculated that the decline was triggered by an external stress such as drought upon a system weakened by air pollution, including acid rain. Regarding such a natural system as "steady" is risky because the climate and other forcing factors are not.

In summary, we have ample evidence that the steady-state theory is simply incorrect. Sensitive watersheds receiving thirteen to sixteen kg/hectare/year wet sulfate deposition or more appear to be changing chemically in a time scale of decades. Waters receiving lower deposition have not been chronically acidified but may be altered and are assumed to be changing chemically over a longer time scale. Resources currently damaged by chemical alteration are very extensive. For example, an estimated 10,000 Canadian lakes have a pH value of less than 5.5. Sixty percent of lakes in the northeastern United States are sensitive to acid rain, and twenty percent are already chemically altered by it. Even if the steady-state theory is partially correct, these damages could be at least partially reversible by emissions reductions. If the theory is incorrect, we face a large future risk of accumulating irreversible damage over a time that is measurable in a few decades. Immediate emissions reductions will slow or avert these damages.
Acid deposition is currently damaging a wide range of resources in eastern North America. The answers to several key questions form the basis for an effective acid deposition control policy. Scientific information currently available enables us to address these issues and outline the general properties of an appropriate control policy.

Acid deposition in eastern North America is caused almost entirely by industrial emissions, with electric power plants as the major source. Sulfur originating in sulfur dioxide emissions deposited in the environment is the major source of watershed acidification, as well as a source of damage to crops, materials, forests, and human health.

In North America, surface waters in sensitive watersheds receiving thirteen to sixteen kg/hectare/year or more of wet sulfate deposition for several decades suffer chronic acidification. Surface waters in watersheds receiving lower deposition levels are not yet chronically acidified but may be chemically altered. Therefore, a reduction in deposition to that level can be expected to protect surface waters from chronic acidification by reversing or slowing chemical change. This target deposition level may also protect the forest-soil complex. Reductions in sulfur dioxide emissions will produce proportional reductions in both wet sulfate deposition and strongly acidic precipitation. Only reductions in sulfur dioxide emissions, as opposed to other pollutant emissions, will produce proportional reductions in total sulfur deposition, the main source of deposited acid. Regional reductions in sulfur dioxide emissions of about fifty percent will be required to attain target deposition levels at all sensitive areas. Additional benefits to some surface waters, as well as forests, may be provided by reductions in emissions of nitrogen oxides.

Long-range transport of sulfur oxides at distances of over 600 miles is a major source of sulfur deposition in sensitive areas. Even the largest local sources do not dominate wet sulfate deposition within even a few tens of kilometers of the source. Furthermore, midwestern sulfur sources dominate the regional sulfur budget. Therefore, the only way to obtain target deposition levels at all sensitive receptors is to obtain large sulfur emissions reductions in the Ohio Basin and midwestern states. Reductions in the NY-NE states alone cannot generally achieve target deposition levels in the NY-NE states. Furthermore, target levels will
not be achieved under emissions projections based on current Clean Air Act regulations.

Some cumulative and irreversible chemical changes appear to occur in northeastern watersheds receiving constant sulfate deposition above the target level. Chemistry in the Southeast will continue to change for a decade or more even at constant acid deposition levels. Therefore, an assumption that surface water chemistry is now stabilized is not appropriate for predicting behavior of watersheds over a few decades. Recent observations in European and American forests suggest the potential exists in the East for rapid change in ecosystems under acid air pollutant stress. These findings underscore the need for expeditious implementation of sulfur dioxide emissions reductions.