United States
Environmental Protection
Agency

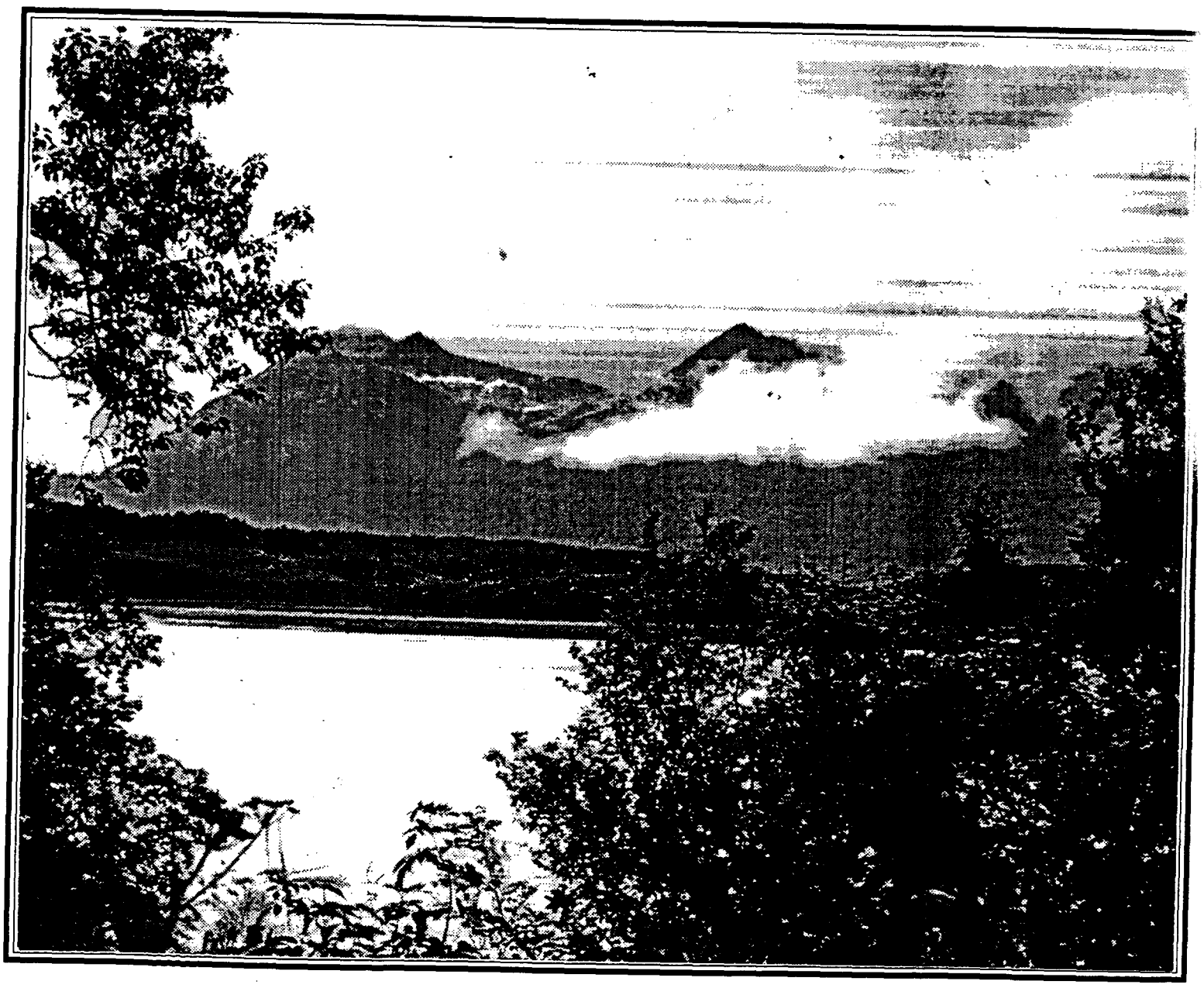
Air And Radiation
(6204J)

EPA 430-R-95-001
February 1995

EPA

Acid Deposition Standard Feasibility Study Report To Congress

Draft For Public Comment



ACKNOWLEDGMENTS

The development of this Acid Deposition Standard Feasibility Study involved the cooperative efforts of individuals within the U.S. Environmental Protection Agency (EPA), especially the Office of Air and Radiation's Acid Rain Division and the Office of Research and Development's Effects Research Laboratory in Corvallis, Oregon, and Atmospheric Research Exposure and Assessment Laboratory in Research Triangle Park, North Carolina. Many individuals at EPA, particularly in the Office of Air Quality Planning and Standards, contributed useful comments to this report. EPA also acknowledges The Cadmus Group, Inc., for their assistance in preparing this report under Contract Number 68-D2-0168.

TABLE OF CONTENTS

LIST OF EXHIBITS

LIST OF ACRONYMS

ADIR	Adirondack Mountain region
ADOM	Acid Deposition and Oxidants Model
AL_{im}	inorganic monomeric aluminum
ANC	acid neutralizing capacity
AQRV	Air Quality Related Values
BACT	best available control technology
BEA	Bureau of Economic Affairs
Btu	British thermal unit
Ca^{2+}	calcium
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CCE	Coordination Center for Effects
CCT	Clean Coal Technology
CEUM	Coal and Electric Utilities Model
Cl^-	chlorine
cm	centimeter
CO	carbon monoxide
DDRP	Direct Delayed Response Project
DOE	Department of Energy
DOI	Department of the Interior
dv	deciview
EMEFS	Eulerian Model Evaluation Field Study
EPA	U.S. Environmental Protection Agency
FIP	Federal Implementation Plan
H^+	hydrogen ion
H_2O_2	hydrogen peroxide
ha	hectare
H_2SO_4	sulfuric acid
HCHO	formaldehyde
HNO_3	nitric acid
IMPROVE	Interagency Monitoring of Protected Visual Environments
kg	kilogram
km	kilometer
LNB	low-NO_x burner
LRTAP	Long-Range Transboundary Air Pollution
LTM	Long-Term Monitoring
m	meter
M-APP	mid-Appalachian region
Mg^{2+}	magnesium
mi	mile
MM4	Mesoscale Model
N	nitrogen
NAAQS	National Ambient Air Quality Standard
NADB	National Allowance Data Base
NAPAP	National Acid Precipitation Assessment Program
NAS	National Academy of Sciences
NBS	Nitrogen Bounding Study
NH_3	ammonia
NH_4^+	ammonium ion
NO	nitric oxide
NO_2	nitrogen dioxide
NO_3^-	nitrate
NO_x	nitrogen oxide
NRC	National Research Council
NSPS	New Source Performance Standard
NSS	National Stream Survey
NSWS	National Surface Water Survey
NURF	National Unit Reference File
NYSDEC	New York State Department of Environmental Conservation
O_3	ozone
PAN	peroxyacetyl nitrate
PM_{10}	particulate matter smaller than 10 micrometers
PO_4^{3+}	phosphate
ppm	parts per million
PSD	prevention of significant deterioration
RADM	Regional Acid Deposition Model
RIA	Regulatory Impact Analysis
S	sulfur
SBRP	Southern Blue Ridge Province region
SCR	selective catalytic reduction
SIP	State Implementation Plan
SNCR	selective non-catalytic reduction
SO_2	sulfur dioxide
SO_4^{2-}	sulfate

SOMA	Sulfur Oxide Management Area	μeq/l	microequivalents per liter
SOS/T	state-of-science/technology	μg/l	micrograms per liter
SO_x	sulfur oxide	μm	micrometer
UNECE	United Nations Economic Commission for Europe	4DDA	four-dimensional data assimilation
yr	year		

EXECUTIVE SUMMARY

Scientific evidence has shown that atmospheric deposition of sulfur and nitrogen compounds can adversely affect ecosystems. Observed effects include acidification of surface waters and damage to high-elevation red spruce forests in the United States. Title IV of the Clean Air Act Amendments of 1990 (CAAA or the Act) addresses the problem of adverse effects on ecosystems from acidic rain by mandating reductions in emissions of sulfur and nitrogen oxides the major precursors of acidic deposition. Coupled with Titles I and II of the Act which address new and existing stationary and mobile sources of sulfur and nitrogen oxides, implementation of Title IV is expected to provide significant benefits to the United States and Canada, including decreases in the acidity of lakes and streams, concomitant improvements in fish population diversity and health, decreases in soil degradation and forest stress, improvements in visibility (especially to scenic vistas), decreases in damage to materials and cultural resources, and a reduction in adverse human health effects. Congress included Section 404 in Title IV (Appendix B of the Act) which requires the Environmental Protection Agency (EPA or the Agency) to provide a report to Congress on the feasibility and effectiveness of an acid deposition standard to protect sensitive and critically sensitive aquatic and terrestrial resources. Specifically, Congress listed six areas to be addressed in the report:

- *Identification of sensitive and critically sensitive aquatic and terrestrial resources in the U.S. and Canada which may be affected by the deposition of acidic compounds;*
- *Description and specification of a numeric value for an acid deposition standard sufficient to protect such resources;*
- *Description of the use of such standard or standards in other Nations or by any of the several States in acidic deposition control programs;*
- *Description of measures that would be needed to integrate such standard or standards with the control program required by Title IV of the Clean Air Act;*
- *Description of the state of knowledge with respect to source-receptor relationships necessary to develop a control program on such standard or standards and additional research that is on-going or would be needed to make such a control program feasible;*
- *Description of impediments to implementation of such control program and the cost-effectiveness of deposition standards compared to other control strategies including ambient air quality standards, new source performance standards and the requirements of Title IV of the Clean Air Act.*

This report fulfills the requirement of Section 404 by integrating state-of-the-art ecological effects research, emissions and source-receptor modeling work, and evaluation of implementation and cost issues to address the six areas and other issues related to the feasibility of establishing and implementing an acid deposition standard or standards.

RESOURCES MOST AT RISK FROM ACIDIC DEPOSITION

The natural resources most at risk from acidic deposition are aquatic systems and high-elevation red spruce forests in the eastern United States and Canada. Although many surface waters in western North America are equally or more sensitive than aquatic systems in the East, deposition levels in the West are sufficiently low that the risk of chronic acidification to these resources is low at present and is expected to remain low in the foreseeable future. Research conducted under the auspices of the National Acid Precipitation Assessment Program (NAPAP) concluded that regions in the United States most at risk from continued acidic deposition are located along the Appalachian Mountain chain stretching from the Adirondacks in New York to the Southern Blue Ridge in Georgia. Target populations of Adirondack lakes, mid-Appalachian streams, and Southern Blue Ridge streams, for which model projections can be reasonably extrapolated, were selected for detailed analysis in this study because they represent areas that receive fairly high levels of acidic deposition, have the best historical data, and have been studied extensively by scientists.

CAAA PROVIDES CLEAR BENEFITS TO SURFACE WATERS

Modeling analysis indicates that sulfur deposition reductions mandated by Title IV of the Act will have clear benefits to sensitive surface waters. Exhibits I–III show the percent of target lakes or streams in each sensitive region projected to be chronically acidic (acid neutralizing capacity [ANC]≤0 μeq/l) by 2040 with and without implementation of the Act. The scenarios are described according to the extent and rate of nitrogen impact on that given watershed. (See footnote below.)* In each modeled region, the proportion of targeted acidic and sensitive surface waters would have been higher, in some cases significantly, without the sulfur dioxide (SO_2) reductions and nitrogen oxide controls in the CAAA.

EXHIBIT I. PERCENT OF TARGETED ADIRONDACK LAKES PROJECTED TO BE CHRONICALLY ACIDIC (ANC≤0 μEQ/L) IN 2040

PERCENT OF TARGET POPULATION ADIRONDACK LAKES OBSERVED ACIDIC IN 1984 = 19%

TARGET POPULATION = 700 LAKES

Nitrogen Saturation Model Projections	Percent of Targeted Waters Projected to be Acidic in 2040	
	Without CAAA	With CAAA
Never	25%	11%
250 years	23%	15%
100 years	36%	26%
50 years	50%	43%

EXHIBIT II. PERCENT OF TARGETED MID-APPALACHIAN STREAMS PROJECTED TO BE CHRONICALLY ACIDIC (ANC≤0 μEQ/L) IN 2040

PERCENT OF TARGET POPULATION MID-APPALACHIAN STREAMS OBSERVED ACIDIC IN 1985 = 4%

TARGET POPULATION = 4,300 STREAMS

Nitrogen Saturation Model Projections	Percent of Targeted Waters Projected to be Acidic in 2040	
	Without CAAA	With CAAA
Never	8%	0%
250 years	21%	4%
100 years	23%	5%
50 years	33%	9%

EXHIBIT III. PERCENT OF TARGETED SOUTHERN BLUE RIDGE PROVINCE STREAMS PROJECTED TO BE CHRONICALLY ACIDIC (ANC≤0 μEQ/L) IN 2040

PERCENT OF TARGET POPULATION SOUTHERN BLUE RIDGE PROVINCE STREAMS OBSERVED ACIDIC IN 1985 = 0%

TARGET POPULATION = 1,300 STREAMS

Nitrogen Saturation Model Projections	Percent of Targeted Waters Projected to be Acidic in 2040	
	Without CAAA	With CAAA
Never	0%	0%
250 years	1%	0%
100 years	2%	0%
50 years	13%	4%

FURTHER REDUCTIONS MAY BE NECESSARY FOR FULL PROTECTION

Scientific analysis indicates that nitrogen as well as sulfur deposition plays an important role in chronic and episodic acidification of surface waters and full protection may not be realized without additional reductions in nitrogen as well as sulfur deposition. Model projections indicate that maintaining the proportion of chronically acidic target surface waters in the Adirondacks near proportions observed in 1984 may require reducing anthropogenic sulfur and nitrogen deposition by 40 to 50 percent or more below levels achieved by the CAAA (assuming 100 years to nitrogen saturation). In the mid-Appalachians, implementation of the CAAA should maintain 1985 proportions of chronically acidic target streams if the time to nitrogen saturation is 250 years or longer; more rapid nitrogen saturation (in the range of 100 years) may require reductions in anthropogenic sulfur and nitrogen deposition by 25 percent below levels achieved by the CAAA. With implementation of the CAAA, no chronically acidic streams are expected within the Southern Blue Ridge target population. Another useful measure is the sensitivity of a lake or stream to becoming acidic (i.e., ANC≤50 μeq/l). Use of this measure (as described in Chapter 2) also indicated that further deposition reductions may be necessary for full protection of target sensitive surface waters.

* Nitrogen saturation is a measure of the capacity of biological processes in a watershed to incorporate nitrogen into organic matter. As this capacity is used up, nitrogen losses from watersheds increase, principally in the form of nitrate leaching. The time to nitrogen saturation can vary among regions due to differences in temperature, moisture, length of growing season, soil fertility, forest age, and historic nitrogen deposition. Currently, uncertainty regarding times to nitrogen watershed saturation in each sensitive region is significant.

ACIDIC DEPOSITION AND EPISODIC ACIDIFICATION

Episodic acidification occurs when pulses of acidic waters enter lakes and streams during stormwater runoff and spring snowmelt. Both sulfates and nitrates originating from atmospheric deposition contribute significantly to episodic acidification events. Rapid, acutely toxic changes in surface water chemistry often occur at the most biologically significant time of year (i.e., during spawning and reproduction). Significantly more lakes and streams become episodically acidic than are chronically acidic. Recent analyses have shown that for the worst episode that may occur during any year, the number of lakes or streams that were acidic during that episode in the Adirondacks is approximately 3.5 times the number found to be chronically acidic. Thus, for the Adirondacks, approximately 70 percent of the target population lakes are at risk of episodic acidification at least once during each year. For the mid-Appalachian streams, approximately 30 percent of the target population stream reaches are likely to be acidic during the worst episode. This is roughly 7 times the number of chronically acidic stream reaches. Due to data limitations, comparable analyses are not possible for streams in the Southern Blue Ridge. Lower levels of acidic deposition will lower the number and severity of acidic and toxic episodes driven by sulfate and nitrate.

EMISSIONS TRADING IS COST-EFFECTIVE AND MAINTAINS ENVIRONMENTAL BENEFITS

A recently released General Accounting Office report estimated that the allowance trading program will reduce control costs by over 40 percent and up to 70 percent if the trading program is used to the fullest extent.† Atmospheric modeling of sulfur deposition projects no more than a 10 percent difference in deposition in 2010 with and without trading. Over most of the eastern United States, the difference in deposition is less than 5 percent, and there is no difference projected for eastern Canada. Exhibit IV is a map that shows the projected annual average difference in sulfur deposition between trading and no trading over the eastern United States and Canada. Variations in deposition of less than 10 percent are not projected to result in measurable ecological impacts. Therefore, while the allowance trading program is expected to reduce costs of control, it is not projected to have a measurable negative environmental impact.

SULFUR EMISSIONS AND DEPOSITION LEVELS

Exhibit V compares deposition levels produced by several sulfur dioxide emissions scenarios. The additional reduction scenarios were chosen to illustrate the effect of further emissions reductions and to serve as examples for cost and implementation analyses; they do not represent a reduction necessary to meet any particular target load. In comparison with 1980 deposition levels, implementation of the CAAA is projected to reduce deposition by 30 to 40 percent by 2010. Exhibit VI shows the projected percentage decrease in sulfur deposition between 1980 and 2010 with full implementation of Title IV. If an additional 50 percent reduction in utility and industrial sulfur dioxide emissions beyond the CAAA were to occur, then sulfur deposition would be reduced by about 60 percent compared to 1980.

NATIONAL OR TARGETED EMISSIONS REDUCTIONS

To achieve an acid deposition standard for a particular sensitive area, some have suggested targeting emissions reductions, rather than reducing national emissions. By 2010, Title IV will produce the largest emissions reductions in the highest emitting regions (i.e., Ohio, Indiana, West Virginia, and western Pennsylvania). An analysis of geographically targeted emissions reductions using the Regional Acid Deposition Model (RADM) shows that to achieve deposition reductions beyond the CAAA (equivalent to those achieved by a 50 percent SO_2 emissions reduction) in sensitive receptor regions, zones targeted for emissions reductions would need to include 6 to 11 states and require source- (region-) specific, sulfur dioxide reductions of about 95 percent. To achieve deposition loadings in all 3 sensitive receptor regions equivalent to that produced by an approximate 50 percent reduction in sulfur dioxide emissions, both geographically targeted and national emissions reductions strategies would require about the same total emissions reductions at about the same total cost. Thus, relative to national emissions reductions, there is no economic or environmental advantage to geographically targeting regions for emissions reductions.

† U.S. General Accounting Office. December. 1994. Air Pollution Allowance Trading Offers an Opportunity to Reduce Emissions at Less Cost. Washington, DC.

EXHIBIT IV. ANNUAL AVERAGE RADM TOTAL SULFUR DEPOSITION (KG-S/HA) IN 2010: DIFFERENCE IN DEPOSITION BETWEEN IMPLEMENTATION OF THE CAAA WITH AND WITHOUT TRADING

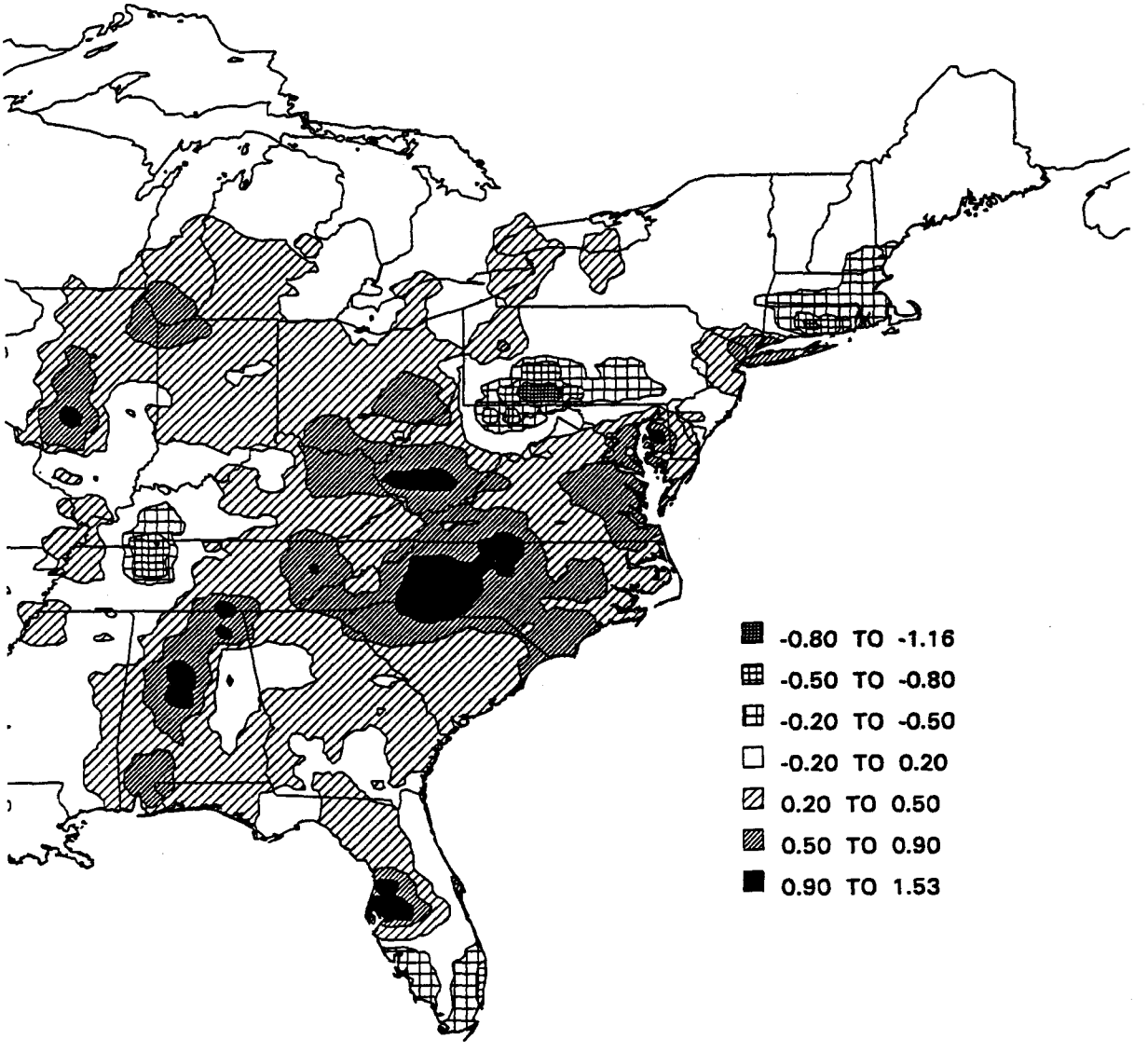
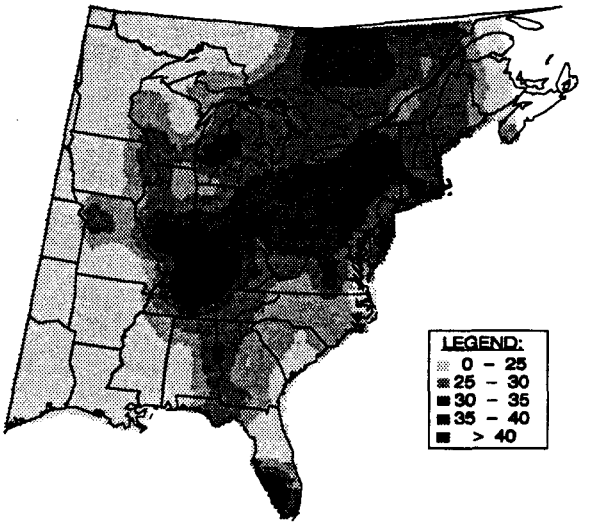


EXHIBIT V. SULFUR DEPOSITION TO SENSITIVE REGIONS UNDER VARIOUS SO_2 EMISSIONS SCENARIOS

Emissions Scenario	Annual Average Deposition Level (kg-S/ha)		
	Adirondacks	Mid-Appalachi-ans	Southern Blue Ridge
1980	11	19	14
1985	9.8	17	13
2010 after CAAA implementation	6.9	11	9.7
CAAA plus additional 50% utility SO_2 reduction	5.5	8.1	6.8
CAAA plus additional 50% utility and industrial SO_2 reduction	4.7	6.9	5.5

EXHIBIT VI. PERCENTAGE REDUCTIONS IN SULFUR DEPOSITION FROM 1980 TO 2010 FROM IMPLEMENTATION OF THE CAAA AND CANADIAN ACID RAIN PROGRAM



IMPLEMENTING AN ACID DEPOSITION STANDARD

In order to determine the effectiveness of an acid deposition standard for protecting sensitive resources, it is necessary to describe how the standard would be implemented.

The study describes two basic approaches to using an acid deposition standard. Under the first approach, EPA would set a standard or standards, either using existing authority or seeking further authority from Congress to set such standards and provide deadlines for their attainment. Then, similar to Title I, states would determine source-specific limits using source-receptor models and technical and cost analyses, incorporate those limits in State Implementation Plans (SIPs), and enforce them. If one or more states failed to do the above, EPA would promulgate a Federal Implementation Plan (FIP).

Under the second approach, Congress would direct EPA to set a deposition standard or standards and to determine the national (or regional) emissions levels for sulfur dioxide and nitrogen oxides that would meet those standards. Congress would then set an emissions cap and allowance allocations for nitrogen oxides and, if necessary, adjust the cap for sulfur dioxide in Title IV, and provide a timetable for meeting the new caps. EPA would use Title IV provisions to implement the emissions program.

To provide a rough comparison of the cost-effectiveness of the two approaches for sulfur reductions, estimates were made of the cost of achieving the same reduction in sulfur deposition from utility sources at the three sensitive areas under each approach. Total compliance costs were similar, although the national emissions reduction approach resulted in slightly larger and more widespread emissions reductions which may provide greater ancillary benefits for human health and visibility protection. The costs of further emissions reductions characterized in this report could lead to costs that are more than double those of the current acid rain control program, but the benefits would be in multiple effects areas.

FEASIBILITY AND EFFECTIVENESS OF AN ACID DEPOSITION STANDARD

The purpose of this study was to provide Congress with a report on the feasibility and effectiveness of an acid deposition standard or standards to protect sensitive aquatic and terrestrial resources. Based on current scientific understanding of the effects of sulfur and nitrogen on aquatic resources, it would be feasible to set sulfur and nitrogen deposition standards to protect aquatic resources, but uncertainty remains high as to the impact of nitrogen. Further research could lower that uncertainty. It would also be helpful to have guidance from Congress or the public on the degree of protection desired, e.g., to protect every aquatic resource from any adverse effect, or to protect 95 percent of sensitive resources from chronic anthropogenic acidification.

The effectiveness of an acid deposition standard depends heavily on the approach used to implement it. Although the two basic approaches discussed in this report could have similar compliance costs and effects on aquatic resources, the national market-based emissions reduction approach could have greater benefits for human health and visibility, is more compatible with the existing Title IV, and is more likely to be implemented. The likelihood of achieving deposition reductions is viewed as a critical factor in judging effectiveness.

CHAPTER 1

INTRODUCTION

Title IV of the Clean Air Act Amendments of 1990 (CAAA or the Act) addresses the problem of adverse effects on ecosystems from acid rain by mandating reductions in emissions of sulfur and nitrogen oxides—the major precursors of acid rain. Coupled with Titles I and II of the Act, which address new and existing stationary and mobile sources of sulfur and nitrogen oxides, implementation of Title IV is expected to provide significant benefits to the United States and Canada. Those benefits include decreases in the acidity of lakes and streams, concomitant improvements in fish population diversity and health, decreases in soil degradation and forest stress, improvements in visibility (especially to scenic vistas), decreases in damage to materials and cultural resources, and a reduction in adverse human health effects. Congress included Section 404 in Title IV (Appendix B of the Act) which requires the U.S. Environmental Protection Agency (EPA or the Agency) to provide a report to Congress on the feasibility and effectiveness of an acid deposition standard to protect sensitive and critically sensitive aquatic and terrestrial resources. Specifically, Congress listed six areas to be addressed in the report:

- *Identification of sensitive and critically sensitive aquatic and terrestrial resources in the U.S. and Canada which may be affected by the deposition of acidic compounds;*
- *Description and specification of a numeric value for an acid deposition standard sufficient to protect such resources;*
- *Description of the use of such standards or standards in other Nations or by any of the several States in acidic deposition control programs;*
- *Description of measures that would be needed to integrate such standard or standards with the control program required by Title IV of the Clean Air Act;*
- *Description of the state of knowledge with respect to source-receptor relationships necessary to develop a control program on such standard or standards and additional research that is on-going or would be needed to make such a control program feasible;*
- *Description of impediments to implementation of such control program and the cost-effectiveness of deposition standards compared to other control strategies including ambient air quality standards, new source performance standards and the requirements of Title IV of the Clean Air Act.*

To achieve significant reductions in emissions of sulfur and nitrogen oxides, Title IV targets emissions from electric utilities—the major source of sulfur dioxide (SO_2) emissions and a major source of nitrogen oxide (NO_x) emissions. Annual emissions of SO_2 are to be reduced by 10 million tons from 1980 levels through an innovative market-based allowance trading program. The program established an SO_2 allowance trading system that allows utilities to minimize the cost of complying with SO_2 emissions reduction requirements, while maintaining a cap on SO_2 emissions from utilities. The trading program encourages energy conservation and technological innovation, which should yield pollution prevention benefits and minimize compliance costs.

Annual allowances for SO_2 emissions have been allocated to affected utility units based on their historic emissions and fuel use. Each allowance permits a utility to emit 1 ton of SO_2. Each unit must hold a sufficient number of allowances at the end of the year to cover its emissions for that year. Emissions reductions will be implemented for 263 units under Phase I beginning in 1995 and for approximately 2,200 units affected under Phase II in 2000. Utilities may buy, sell, trade, or save allowances for future use. When the program is fully implemented in 2010, nationwide emissions of SO_2 from affected utilities (i.e., units generating over 25 MW) will be capped at 8.95 million tons per year. In addition, nationwide emissions of SO_2 from industrial sources are capped at 5.6 million tons per year. These emissions are not included in the allowance trading program, but some indus-

trial sources may be allowed to elect to participate in the program under rules currently being developed by EPA.

Title IV also specifies that standards be set for NO_x emissions from utility boilers, with the goal of reducing nationwide emissions by 2 million tons from 1980 levels. Unlike the SO_2 program, the NO_x program does not use a tradable allowance system and does not cap emissions, but instead calls for low-NO_x burner technology to reduce emissions.

Concerns exist regarding how allowance trading will affect protection of sensitive aquatic and terrestrial resources. Some critics argue that the cautious nature of the electric utility industry and local pressure in high-sulfur coal regions to continue use of regional coals to preserve local economies will not allow trading to achieve economically meaningful benefits. Others argue that extensive trading could result in a geographic distribution of emissions that would prevent achieving the Act's goal of reducing the effects of acidic deposition in sensitive areas and that emissions levels resulting in no adverse effects are necessary for protection.

The process for determining the degree of protection afforded by Title IV to sensitive and critically sensitive aquatic and terrestrial resources is complicated by a number of scientific and technical uncertainties. For example, there are gaps in ecological effects research, particularly regarding nitrogen cycling and retention in forested watersheds. The scientific community is still learning how multiple impacts of sulfur and nitrogen acidic deposition affect ecosystems. In addition, meteorological variability, uncertainties in emissions inventories, and the complexity of atmospheric chemistry limit the ability to relate specific ecosystem damage to specific point sources.

The purpose of this study is to integrate state-of-the-art ecological effects research, emissions and source-receptor modeling work, and implementation and cost issues to consider the feasibility of setting and implementing a standard to protect aquatic and terrestrial resources from the effects of acidic deposition. This report addresses three broad themes:

1. *What acidic deposition levels are necessary to protect sensitive regions?*
2. *What degree of protection is provided by Title IV? What is the residual risk? What additional emissions limitations would be required to protect sensitive regions?*
3. *How would an acid deposition standard(s) be implemented? What are the different implementation approaches? What are their relative feasibility and effectiveness?*

A common thread running through each is uncertainty in (1) data and models, (2) future ecosystem behavior, and (3) future economic and policy decisions that may influence decisions regarding feasibility.

WHAT ACIDIC DEPOSITION LEVELS ARE NECESSARY TO PROTECT SENSITIVE REGIONS?

The report outlined in Section 404 (Appendix B) of the Act requires identification of sensitive aquatic and terrestrial resources and description of the nature and numerical value for a deposition standard that would protect these resources. This report identifies sensitive resources and describes options for and the nature of a protective goal (i.e., deposition standard); scientific uncertainties associated with the response of specific sensitive regions to acidic deposition, however, make designation of a numerical value for a deposition standard that would protect each sensitive region difficult at this time. Chapter 2 of this feasibility study brings together the most current scientific understanding regarding the relationship between acidic deposition and ecological effects, specifically effects on watersheds. The information comes from research conducted by EPA's Office of Research and Development, peer-reviewed literature, and efforts to define appropriate acid deposition standards in the United States and other countries. Best understood from the scientific point of view is the relationship between acidic deposition of sulfur and its effects on stream and lake ecosystems. Effects of nitrogen deposition on aquatic systems and of combined sulfur and nitrogen deposition on terrestrial systems are less clear and poorly quantified for resources in the United States.

Regions of North America differ in their sensitivity to acidic deposition (i.e., ability of a watershed to buffer acidity) and in the amount of acidic deposition they receive. Some parts of the eastern United States are highly sensitive and chronically or episodically receive damaging concentrations of acidic deposition. Other sensitive regions, such as the western United States, are unlikely to suffer adverse chronic effects at current or projected rates of acidic deposition. Certain high-elevation western lakes, however, are subject to episodes of

acidic deposition. Chapter 2 identifies sensitive aquatic and terrestrial resources in specific regions of the United States and describes the effects caused by acidic deposition in each region. Aquatic resources of concern include fish and other species, as well as the water quality of lakes and streams. Terrestrial resources of primary concern include trees and forest soils.

The relative contributions and importance of sulfur- and nitrogen-containing compounds to the effects of acidic deposition differ among regions. The importance of each group of compounds depends on its relative deposition level and on the capacity of individual watersheds to retain deposited nitrogen and sulfur. Sulfur appears to be the principal cause of ongoing, chronic acidification of aquatic systems within most affected areas in eastern North America. The importance of nitrogen deposition, however, cannot be overlooked for several reasons: visibility in many areas of the West is degraded more by nitrogen than sulfur deposition; nitrogen, as well as sulfur, produces episodic surface water acidification effects, especially during spring snowmelts; and some watersheds in the Northeast may be approaching the limit of their ability to sequester nitrogen, leading to increased acidification from nitrogen deposition.

Chapter 2 assesses these issues by analyzing available scientific data within a risk-based context and produces a set of environmental goals. The analyses concentrate on the three regions in the United States most extensively characterized: the Adirondacks, the mid-Appalachians, and the Southern Blue Ridge Province, each of which is subject to deposition from sources in the East. Knowledge of current and historic differences in deposition levels and watershed sensitivities in these three regions makes it possible to discern differences in ongoing effects and remaining risk for each. Risks for other regions of the United States and Canada are also described, but in a more qualitative sense. Effects-based (critical and target load) control strategies and approaches adopted by Europe, Canada, and several states in the United States are also discussed. The importance of considering the effects of nitrogen deposition on both eutrophication of estuarine bodies[1] and acidification of surface waters is also discussed. (Note that an effects-based analysis and development of an acid deposition standard or standards does not necessarily imply emissions reductions associated with implementation of a standard or target loads.)

Although this report focuses on aquatic and terrestrial systems at risk, acidic deposition and its precursor emissions also can adversely affect visibility, human health, and materials. Decreasing acidic deposition can also provide benefits in these areas. Visibility, especially in the eastern United States, is markedly degraded by sulfate particles in the atmosphere. Human health effects from exposure to SO_2, NO_2, and ozone (O_3, formed by chemical reactions involving nitrogen dioxide) are well known, and effects from particulate matter, including acidic aerosols, are documented as well. Damage to materials and cultural resources by acidic deposition has been documented by the National Acid Precipitation Assessment Program (NAPAP).[2] Visibility degradation has been addressed more fully in another Report to Congress[3] and is covered under Section 169A of the Act. Also, primary National Ambient Air Quality Standards (NAAQS) have been established to protect the public health from adverse effects of criteria pollutants, including SO_2, NO_2, particulate matter (including sulfates and nitrates), and O_3. Nevertheless, any control program or standard established to reduce acidic deposition will also provide benefits in these other related areas. Chapter 4 of this report summarizes these potential benefits to visibility, human health, and materials.

WHAT DEGREE OF PROTECTION IS PROVIDED BY TITLE IV? WHAT IS THE RESIDUAL RISK? WHAT ADDITIONAL EMISSIONS LIMITATIONS WOULD BE REQUIRED TO PROTECT SENSITIVE REGIONS?

The complex relationship between emissions and deposition depends on a great number of physical, chemical, and biological processes. Acidic deposition results from a complex series of interactions among chemicals in the atmosphere. Airborne sulfur and nitrogen species can be transported hundreds of kilometers by meteorological forces. During transport these species can remain unchanged or react with other atmospheric pollutants, such as

[1] U.S. Environmental Protection Agency. May 1994. *Deposition of Air Pollutants to the Great Waters.* First Report to Congress. EPA-453/R-93-055.

[2] Irving, P.M., ed. 1991 *Acidic Deposition: State of Science and Technology.* Summary Report. National Acid Precipitation Assessment Program. Washington, DC.

[3] Office of Air Quality Planning and Standards. October 1993. *Effects of the 1990 Clean Air Act Amendments on Visibility in Class I Areas: An EPA Report to Congress.* U.S. Environmental Protection Agency, Washington, DC.

volatile organic compounds (VOCs), to form new compounds, some of which are acidic. These pollutants are then deposited to the earth through either wet or dry deposition. To understand the environmental impact of the Act and to develop and analyze strategies to reduce the effects of acidic deposition, the relationship between emissions and deposition (i.e., the source-receptor relationship) should be addressed not only in the present, but also in the future.

SO_2 and NO_x reduction mandates established by Title IV provide for a nationwide decrease in acidic deposition precursors. Geographic or regional restrictions do not exist. The market-based allowance trading program promotes the most cost-effective strategy for achieving SO_2 reductions, rather than requiring a specific type of control on certain sources. Variation in sensitivity to acidic deposition among geographic regions raises the question of whether targeted or regional standards are needed to protect sensitive resources. Before such a question can be answered, determining the level of protection that will be provided by full implementation of Title IV in 2010 and in subsequent years is necessary.

To answer questions regarding the effectiveness of Title IV in protecting sensitive areas (i.e., the residual risk after implementation of Title IV) and the impact of additional control, several alternative emissions scenarios are developed in Chapter 3:

- A scenario that achieves the SO_2 emissions reductions mandated by the Act,
- A scenario to assess the environmental impact of trading SO_2 allowances, and
- Scenarios that achieve additional reductions of SO_2 and NO_x emissions from utilities and industrial sources beyond those required by the Act.

The Regional Acid Deposition Model (RADM)[4] is used to translate each emissions scenario to deposition values for the eastern United States. Deposition of sulfur and nitrogen species are then compared for each scenario, with particular emphasis on the three key sensitive areas—the Adirondacks, the mid-Appalachians, and the Southern Blue Ridge Province.

HOW WOULD AN ACID DEPOSITION STANDARD(S) BE IMPLEMENTED? WHAT ARE THE DIFFERENT IMPLEMENTATION APPROACHES? WHAT ARE THE FEASIBILITY AND EFFECTIVENESS RELATIVE TO OTHER APPROACHES?

In Chapter 5, two broad approaches are reviewed for degree of protection, geographic coverage, implementation difficulty, and cost. The approaches follow the emissions reductions scenarios modeled in Chapter 3. The two broad implementation approaches are (1) a national, emissions-oriented, market-based approach and (2) a regional, standard-oriented, source- (region-) specific limit approach. Control of both utility and industrial sources is assessed.

A variety of factors should be considered in implementing an acid deposition standard. To be successful, an implementation approach must have clear goals and must provide certainty as to the responsibilities of the regulated community, EPA, and states. Chapter 5 identifies and describes the factors that may affect implementation of a standard under both national and regional approaches. Four general categories of factors are considered:

- STATUTORY AUTHORITY: A first step in assessing the feasibility of an acid deposition standard is determining whether EPA has authority to implement a standard under the existing CAAA. Is existing authority adequate, or would Congress need to provide additional authority necessary to implement an acid deposition standard or standards?
- ADMINISTRATION/COMPLIANCE: How enforceable and administratively complex are alternative regulatory approaches? How would the approach be administered and enforced? Would new administrative entities be needed? What level of federal and state resources would be needed?
- INTERACTION AND INTEGRATION WITH OTHER ENVIRONMENTAL PROGRAMS: An acid deposition standard may impose additional limits on SO_2 and NO_x emissions from point, area, and/or mobile sources. Existing federal, state, and local regulations (including the Title IV Acid Rain Program, Title I Ambient Air Standards, and Title II Mobile Source regulations at the federal level) ad-

[4] Chang, J.S., P.B. Middleton, W.R. Stockwell, C.J. Walcek, J.E. Pleim, H.H. Lansford, F.S. Binkowski, S. Madronich, N.L. Seaman, and D.R. Stauffer. December 1990. *The Regional Acid Deposition Model and Engineering Model.* NAPAP SOS/T Report 4. In: Acidic Deposition: State of Science and Technology. National Acid Precipitation Assessment Program.

dress emissions from these sources. What effect would implementation of an acid deposition standard have on these and other environmental programs?

- Economic Impacts: What would be the costs and economic impacts of an acid deposition standard to the regulated community, as well as the national and local economies?

Chapter 6 integrates analyses of environmental goals, emissions reductions, and implementation issues and provides conclusions concerning the feasibility of developing and implementing a standard or standards for acidic deposition.

CHAPTER 2

ENVIRONMENTAL GOALS

2.1 INTRODUCTION

Title IV of the 1990 Clean Air Act Amendments (CAAA) addresses the problem of adverse effects to environmental resources from acidic deposition by mandating nationwide reductions in emissions of sulfur and nitrogen oxides from electric utility generating units, the major contributor to acidic deposition. While reductions in total emissions will benefit many aquatic and terrestrial resources, Congress mandated a study of whether more specific acid deposition standards may be appropriate. Under Section 404 (Appendix B) of the CAAA, EPA must assess the feasibility and effectiveness of establishing an acid deposition standard, or standards, to protect sensitive aquatic and terrestrial resources. This chapter addresses three specific Section 404 requirements:

- *Identification of the sensitive and critically sensitive aquatic and terrestrial resources in the United States and Canada which may be affected by the deposition of acidic compounds;*
- *Description of the nature and numerical value of a deposition standard or standards that would be sufficient to protect such resources;*
- *Description of the use of such standard or standards in other Nations or by any of the several States in acidic deposition control programs.*

Section 2.2 of this report reviews surface water acidification and recovery processes. The two most common measures of surface water acidification are pH and acid neutralizing capacity (ANC). Low ANC is a common indicator of sensitivity to acidification; other parameters, including pH, dissolved aluminum, and sensitive species, also provide useful information on resource health. Atmospheric deposition of sulfur and nitrogen compounds that form acids is the principal cause of surface water acidification effects. Most recent attention has focused on the effects and control of sulfur deposition (Section 2.2.1). While many studies have focused primarily on long-term acidification processes, recent EPA research supports the contention that short-term acidification caused by rainstorms and snowmelt may often be the initial cause of many of the most severe acidification effects in streams. Consideration of acid deposition standards may take into account implications to both the long- and short-term acidification processes (Section 2.2.2). Recent research also indicates that acidification effects caused by nitrogen deposition are increasingly important in some areas. The increasing degree of nitrogen saturation in some watersheds is leading to long-term and short-term increases in nitrate concentration and concomitant acidification of some surface waters (Section 2.2.3). Section 2.2.4 notes that a number of studies indicate that surface water acidification can be reversed by reducing emissions and, at least temporarily, by practices such as liming (e.g., the application of powdered limestone); however, restoration of ecological systems to their predisturbance conditions may not be possible.

Section 2.3 introduces a risk-based approach to assessing the need for an acid deposition standard. Alternative approaches for defining resource sensitivities are reviewed, and environmental and land-use characteristics affecting these sensitivities are described (Section 2.3.1). Section 2.3.2 emphasizes that using a risk-based approach requires assessing four central concerns: (1) sensitivities of potentially affected resources; (2) factors extrinsic to selected resources that may alter their sensitivities; (3) geographic location of the selected resources; and (4) exposure intensity, duration, and timing of acidic deposition at the selected locations.

Section 2.4 addresses the first Congressional requirement listed above. Section 2.4.1 emphasizes that assessments of the need for acid deposition standards should focus primarily on potential benefits to sensitive aquatic resources in six regions of the eastern half of the United States and to sensitive stands of red spruce at high elevations in two of those regions. An EPA-sponsored literature review confirmed that the potential effects of nitrogen deposition is an increasing concern in the western United States as well (Section 2.4.2). In the area of Canada roughly south of James Bay and east of the Manitoba-Ontario border, resource concerns similar to concerns

for the eastern United States are emphasized (Section 2.4.3).

Section 2.5 addresses the second Congressional requirement by describing the potential need to protect acid-sensitive resources and the potential benefits derived from additional control of acidic deposition. Simulation modeling is the best available way to project future ecological effects of possible changes in deposition rates. This approach is not without limitations, however, as results carry considerable uncertainty (Section 2.5.1). Two major EPA effects modeling studies have been completed. The first study, conducted under the National Acid Precipitation Assessment Program (NAPAP), projected the impact of sulfur deposition on long-term soil and surface water acidification, with consequent loss of aquatic habitat for sensitive fish species, in three broad geographical regions of the eastern United States. Adverse effects were projected to continue unless sulfur deposition was reduced, and sufficient reductions in sulfur deposition were projected to likely reverse these effects (Section 2.5.2). The second major EPA modeling study illustrated the role that nitrogen deposition may play as an important cause of soil and water acidification, and its importance was projected as likely to increase in future years unless deposition rates decreased (Section 2.5.3). This study also projected that the 1990 CAAA would provide clear benefits to surface water in three sensitive regions of the eastern United States. The accuracy of the model projections is highly uncertain, however, largely because researchers lack precise estimates of how long it takes a sensitive watershed to become saturated with deposited nitrogen.

In addressing the third Congressional requirement, Section 2.5.4 reviews various acidic deposition criteria and standards that have been developed internationally and by individual states, many of which are being revised as additional and more accurate information becomes available. This section is not, however, a comprehensive list of all state or international efforts. Important ecological and geographical concerns that raise questions about whether the application of deposition standards should take into account regional and seasonal conditions are discussed in Section 2.5.5. Finally, assessments of the need and options for developing deposition standards address concerns related to both sulfur and nitrogen deposition (Section 2.6).

2.2 BASIC RELATIONSHIPS IN SURFACE WATER ACIDIFICATION AND RECOVERY

Understanding the need for and feasibility of establishing acid deposition standards and understanding the sensitivities of resources to acidification, requires a knowledge of how environments assimilate atmospherically deposited acids and acid-forming chemical compounds. This knowledge is key to assessing whether surface water acidification effects are occurring in a region, when these effects began, how extensive the effects are and may become, and the critical periods when these effects may be most severe. This section briefly reviews the process of surface water acidification, important considerations in identifying at-risk resources, episodic acidification, and useful information for setting regional and resource priorities for acidic deposition controls. The section concludes with a brief discussion of the responses of acidified ecosystems to reductions in acidic deposition levels. First, a few common terms and concepts, key to understanding surface water acidification processes, are introduced.

The common measure of acid-base conditions in solutions is the pH scale. On this scale, *neutrality* (i.e., neither acidic nor basic) occurs at pH 7.0; *acidic* conditions have lower values (pH<7.0), while *basic* (also termed *alkaline*) conditions have higher values (pH>7.0). The most acidic conditions occur near pH 0.0 and the most alkaline conditions occur near pH 14.0. On this scale, each full unit decrease in pH (e.g., from 7.0 to 6.0) represents a ten-fold increase in acidity and in the concentration of hydrogen ions that cause acidity.

Some surface waters are naturally acidic. This is largely due to (1) carbon dioxide from the atmosphere dissolving to form carbonic acid and (2) organic acids produced by the decay of dead plant materials. Waters in some bog lakes, for example, can have natural pH levels below 5.0. Similarly, pure rain water and distilled water in equilibrium with atmospheric concentrations of carbon dioxide naturally have pH levels near 5.6. Dissolution of natural organic acids from the atmosphere into rain water has been found to increase rain water acidity and lower pH to near 5.2 in some pristine open ocean areas.

The natural tendency of some surface waters to be acidic is countered by common, alkaline minerals such as limestone that dissolve into them. This dissolution neutralizes the acidity, often producing slightly alkaline conditions (*alkalinization*). The dissolution of many minerals not only neutralizes

acidic conditions in waters, it produces a buffering capacity that enables these waters to maintain near-ambient pH conditions, while allowing their mass of dissolved acids to vary within certain limits. Additional buffering capacity can be produced by solutions of weak acids, including carbonic acid and many organic acids. The extent of acid-base buffering within any natural water is determined by the specific combinations of dissolved materials.

In total, the interaction of these natural acidification, alkalinization, and buffering processes causes the pH in most surface waters to range from about 6.5 to 8.0. Much of the concern about surface water acidification focuses on the effects that may occur with decreases of 0.5 to 2.0 pH units or more (i.e., increasing acid concentrations in the environment by 500 to 10,000 percent or more).

Acid neutralizing capacity (ANC) is the term commonly used to describe the concentration of dissolved compounds present in fresh water that collectively tend to neutralize water pH, creating less acidic and more alkaline conditions. Greater ANC generally correlates with greater buffer capacity in the water. In most fresh waters ANC is determined primarily by concentrations of carbonate and bicarbonate, which generally dissolve into the water from calcium carbonate (the predominant chemical constituent of limestone, for example). Concentrations of borates, phosphates, silicates, sulfides, and organic anions can also contribute to total ANC in surface water. In earlier literature, the term *alkalinity* was often used in place of ANC.[5] In most recent literature, however, alkalinity is used primarily in discussing total dissolved concentrations of bicarbonates, carbonates, and hydroxides in water. The total capacity of a surface water to neutralize acidity can include other chemical and biological processes—the most important of which are the biologically mediated processes of sulfate (SO_4^{2-}) and nitrate (NO_3^-) reduction.

Surface waters with higher ANC are generally more resistant to acidification and have higher pH levels. That is, lakes and streams with ANCs greater than 200 microequivalents per liter (μeq/l) have significantly moderated potential for pH fluctuations below 6.0. Also, they generally have minimal development of acidic water qualities that can be stressful, or even toxic, to aquatic organisms. In turn, waters with ANCs of 50 μeq/l or less tend to be the most sensitive to severe and long-term pH depressions below 6.0, which can produce the most severe effects on aquatic life. The general empirical relationship between pH and ANC was determined during EPA's Nitrogen Bounding Study (NBS) (see Section 2.5.3) for three regions in the eastern United States that contain sensitive ecological resources (Exhibit 1). This exhibit shows, for example, that an ANC of 50 μeq/l correlates approximately to a pH of 6.5 across these regions.

EXHIBIT 1. EMPIRICALLY DETERMINED RELATIONSHIP BETWEEN ANC AND PH FOR THREE SENSITIVE REGIONS, INCLUDING CROSS-REGIONAL MEAN AND STANDARD DEVIATION

ANC (μeq/l)	Empirical pH for Sensitive Regions			Mean pH	Standard Deviation
	Adirondacks	Mid-Appalachians	Southern Blue Ridge		
-10	4.96	4.98	4.95	4.96	0.02
0	5.28	5.30	5.27	5.28	0.02
10	5.69	5.72	5.78	5.73	0.05
40	6.31	6.36	6.53	6.40	0.12
50	6.41	6.47	6.65	6.51	0.12
60	6.50	6.55	6.73	6.59	0.12

Acidic deposition can lead to two kinds of acidification processes. First, over the longer term, the fundamental character of soil and water chemistries can shift to *chronically acidic conditions* due to the input and accumulation of deposited acidic ions. Such conditions can produce adverse environmental effects which may be long-term, chronically toxic, and lethal. Second, *acutely acidic conditions* can rapidly develop during periods leading to, accompanying, or following episodic events, which primarily accompany discharges of storm and snowmelt water runoff.

[5] Drever, J.I. 1982. *Geochemistry of Natural Waters.* Prentice-Hall, Inc., Englewood Cliffs, NJ.

Pulses of highly acidic water flushing into and through soils, streams, and lakes often expose soil and aquatic biota to short-term, *acutely toxic,* lethal chemical conditions.

When considering acidification effects, it is important to recognize that the earliest adverse effects to biological components of an aquatic ecosystem commonly accompany early episodic acidification events. For acid-sensitive fish species, for example, these events often cause complete spawning or recruitment failures. As chronic acidification becomes more pronounced, such effects become more frequent and may result in further impacts to overall species richness. In contrast, for systems recovering from acidification, this sequence reverses as occasions of episodic effects become less and less frequent, until acidification effects apparently end.

As more fully discussed in several of the following sections, available information indicates that surface waters with ANCs≤50 μeq/l include the aquatic resources most sensitive to potential effects from episodic acidification. Thus, ANC is a very important response variable for use in evaluating acidification-related changes in surface waters, particularly streams. As such, ANC is a primary focus of discussion throughout this chapter. The next four subsections review potential chemical relationships, episodic acidification, cumulative effects, and recovery processes associated with soil and water acidification. Biological implications are discussed in reviewing of identification of resource priorities. Additional issues are summarized in Appendix A, Summary of NAPAP reports.

2.2.1 Relationship of Base Cations, Sulfur, and Nitrogen in Surface Water Acidification

Acidic deposition increases total loads of hydrogen ions (H^+) and acidic anions (primarily SO_4^{2-} and NO_3^-) in watersheds. A vast majority of these deposited ions interact within the watersheds, exchanging with and displacing ions of other chemical species from watershed receptors primarily through soil weathering and chemical equilibrium processes in soil waters. Most watershed ions exchanged for deposited ions enter soil water solutions and subsequently drain into streams and lakes.

In a report that provided much of the basis for EPA's modeling research on watershed responses to acidic deposition, the National Academy of Sciences (NAS) identified two geochemical processes as the dominant watershed factors mediating long-term surface water acidification.[6] The first is the rate at which watershed sources exchange base cations, especially calcium (Ca^{2+}) and magnesium (Mg^{2+}), for H^+ through neutralization and buffering processes. Essentially all base cations within a watershed are supplied initially through the relatively slow process of mineral weathering, while much more rapid supplies of base cations can be available through exchange processes within soil solutions and by soil biota. Acidic deposition can accelerate each of these processes.

The second dominant factor that NAS identified as affecting acidification is the capacity of a watershed to retain deposited sulfur-containing compounds. This process is important because a vast majority of atmospherically deposited sulfur is in the form of SO_4^{2-} or other inorganic sulfur-containing compounds that rapidly oxidize to SO_4^{2-}. The process of SO_4^{2-} adsorption by soils directly affects the mobility of SO_4^{2-} in watersheds and, thus, the mobility of assorted base cations and acidic cations (e.g., H^+ and aluminum, Al^{3+}).

The NAS report concluded that the external process of acidic ion deposition balanced against internal watershed processes of base cation supply (i.e., acid assimilation) and SO_4^{2-} adsorption (i.e., anion mobility) critically determine the rates and degrees of long-term acidification of soil and water. The production of base cations and internal retention of sulfur in watersheds can decrease as available supplies of base cations and SO_4^{2-} adsorption abilities are depleted. Surface waters in watersheds with insufficiently available base cation supplies and minimal net annual sulfur retention tend to be at greater risk from acidic deposition.

EPA initiated the Direct Delayed Response Project (DDRP) (see Section 2.5.2) to help understand how these factors interact and affect environmental responses to acidic deposition. This project primarily addressed the question of whether watersheds tend to acidify immediately in proportion to the intensity of deposition (i.e., "direct" acidification) or lag

[6] National Academy of Sciences. 1984. *Acid Deposition: Processes of Lake Acidification, Summary of a Discussion.* National Research Council Commission on Physical Sciences, Mathematics, and Resources. Environmental Studies Board, Panel on Processes of Lake Acidification. National Academy Press, Washington, DC. 11 pp.

in time due to internal watershed processes (i.e., "delayed" acidification).

Unquestionably, watershed processes regulating base cation exchange and retention of atmospherically deposited sulfur are two primary controls on surface water acidification rates that must be understood to allow projection of potential acidic deposition effects. More recent research shows, in addition, that direct projection of surface water acidification rates from acidic deposition also depends upon, and continues to be limited by, major uncertainties regarding the capacities of watersheds to assimilate nitrogen deposition. That is, although NO_3^- is often an important acid anion in acidic deposition, nitrogen is also an essential nutrient in high demand by many physiological processes within organisms. Its frequent scarcity in many environments, relative to other essential nutrients, often limits plant growth and other biological activities. Thus, because nitrogen is a fertilizer that often quickly incorporates into organisms, the ANC of soils and surface waters is relatively unchanged. Consequently, only a generally limited past concern and a narrowly defined research effort has been focused on ecological effects associated with nitrogen deposition in watershed acidification.

An expanding body of recent research, however, shows that nitrogen deposition is an important component and an increasing cause of present and future acidification in some environments. Specifically, there are limits to the amount of nitrogen that can be incorporated into organic matter by biological processes in watersheds. When these processes are saturated (i.e., when nitrogen is no longer the limiting nutrient for biological production and growth), nitrogen losses from watersheds will increase, principally in the form of NO_3^- leaching. Excess NO_3^- in watersheds can lead to depletion of base cations and surface water acidification through the same processes as those involving excess SO_4^{2-}. For example, European forests apparently are becoming nitrogen saturated, and the need for specific additional emissions controls to protect European forests and surface waters from the detrimental effects of excessive nitrogen deposition are being evaluated.[7]

Further, data from Long-Term Monitoring (LTM) sites in the northeastern United States strongly indicate a regional decrease in lake and stream water SO_4^{2-} through 1989 (the end of the period of record assessed), suggesting that sulfur deposition is declining. A concurrent, general increase in lake and stream water NO_3^- concentrations was found primarily in the Adirondack and Catskill Mountains, suggesting that these watersheds may be moving toward watershed nitrogen saturation. Surface water NO_3^- concentrations did not show marked trends for most other areas of the Northeast. Over this same period in the Northeast, both pH and ANC tended to increase, but these trends are weaker than those found for SO_4^{2-} and NO_3^- deposition. For Adirondack lakes, in fact, there appears to be a possible trend of decreasing ANC. Coupling these possible regional ANC trends with the apparent trends for SO_4^{2-} and NO_3^- indicates that surface water acidification effects may be becoming more closely tied to NO_3^- deposition in the Adirondacks and, possibly, other regions of the Northeast. Research is continuing to evaluate more completely this potential shift in surface water acidification relationships.

Of additional concern are episodes of storm flow or snowmelt runoff that can expose organisms to short-term, acutely lethal, acidic water.[8] Episodic events (described in detail in the following section) occurring during spring snowmelt often tend to be the most acidic and contain the highest concentrations of inorganic monomeric aluminum, which is highly toxic to fish.[9] NO_3^- tends to be more mobile in watershed soils at this time of the year because most plants are dormant. This fact and the prevailing cold temperatures through winter and early spring tend to promote increasing NO_3^- accumulations in soil and overlying snowpack. Especially during these periods, snowmelt and storm

[7] Sullivan, T.J. 1993. Whole-ecosystem nitrogen effects research in Europe. *Environmental Science and Technology* 27(8):1482-1486.

[8] Wigington, P.J., Jr., J.P. Baker, D.R. DeWalle, W.A. Kretser, P.S. Murdoch, H.A. Simonin, J. Van Sickle, M.K. McDowell, D.V. Peck, and W.R. Barchet. 1993. *Episodic Acidification of Streams in the Northeastern United States: Chemical and Biological Results of the Episodic Response Project.* EPA/600/R-93/190. Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC.

[9] Baker, J.P., and S.W. Christensen. 1991. Effects of acidification on biological communities in aquatic ecosystems. Pages 83-106 in D.F. Charles (editor). *Acidic Deposition and Aquatic Ecosystems - Regional Case Studies.* Springer-Verlag, New York, NY.

water runoff can flush NO_3^- through the watershed at flow rates that exceed the assimilative capacity of terrestrial plants to capture the rapidly passing nutrients. Cold water temperatures also slow the ability of aquatic organisms to incorporate the newly added NO_3^-. As a result, NO_3^- can be a significant seasonal cause of episodic acidification in surface waters in some regions, often occurring at the most biologically significant time of year (i.e., during spawning and reproduction).

2.2.2 Episodic Acidification

This report primarily focuses on chronic effects to surface waters associated with long-term exposure to acidic deposition, because much past research has emphasized processes leading to long-term chronic acidification. In surface waters that have not completed processes leading to chronic acidification or are in the process of recovering from chronic acidification, the largest impacts of acidic deposition most commonly accompany episodic acidification. *Episodic acidification* (temporary loss of ANC) can occur when pulses of low-ANC or acidic waters enter streams and lakes as the result of rainstorms or snowmelt. Acid anions (i.e., sulfate and nitrate) that reach surface waters during these events may originate from immediate deposition or, more likely, may be the result of prior atmospheric deposition (i.e., the previous year) that has cycled within the watershed and is flushed from the system during the high storm flows. Accompanying the acid anions during leaching are acids or toxic aluminum compounds leached from soils. Both sulfates and nitrates originating from atmospheric deposition may contribute significantly to such episodic acidification events. Episodic acidification can cause lakes and streams that have positive ANC during most of the year to become acidic (ANC≤0 μeq/l) and have high toxic aluminum concentrations for periods of hours to days.

The most severe episodes of acidification occur in the spring. The National Surface Water Survey (NSWS) (described in Section 2.4), however, surveyed lakes in the Adirondacks during the fall. Significantly, more lakes and streams become episodically acidic than are chronically acidic. Most recent estimates indicate that for the worst episode that may occur during any year, the number of lakes or streams that were acidic during that episode in the Adirondacks is approximately 3.5 times the number found to be chronically acidic. Thus, for the Adirondacks, approximately 70 percent of the target population lakes are at risk of episodic acidification at least once during each year. For the mid-Appalachian streams, approximately 30 percent of the target population stream reaches are likely to be acidic during the worst episode. This is roughtly 7 times the number of chronically acidic stream reaches. Due to data limitations, comparable anlayses are not possible for streams in the Southern Blue Ridge. Lower levels of acidic deposition will lower the number and severity of acidic and toxic episodes driven by sulfate and nitrate.

EPA recently completed its *Episodic Response Project.*[10] Major conclusions from that project include:

- Acidic deposition episodes, evidenced by stream water containing elevated SO_4^{2-} and NO_3- concentrations during the episodes, were a common occurrence in the study streams of all three regions investigated (i.e., the Adirondack and Catskill Mountains of New York and the Northern Appalachian Plateau of Pennsylvania).
- Acidic episodes were common in streams of each region wherever and whenever ANC values were 50 μeq/l or less immediately before the episode. When acidic episodes occurred, they were accompanied by depressed pH levels and elevated concentrations of inorganic monomeric aluminum (Al_{im}).
- Elevated concentrations of SO_4^{2-} in Pennsylvania streams and of NO_3^- in Catskill and Adirondack streams augmented natural processes during episodes to produce lower ANC and pH and higher Al_{im} levels than would have occurred due to natural processes alone.
- Even when SO_4^{2-} and NO_3^- concentrations did not markedly increase during episodes, elevated baseline concentrations of SO_4^{2-} in all regions and of NO_3^- in the Catskill and Adirondack streams lowered minimum

[10] Wigington, P.J., Jr., J.P. Baker, D.R. DeWalle, W.A. Kretser, P.S. Murdoch, H.A. Sinonin, J. Van Sickle, M.K. McDowell, D.V. Peck, and W.R. Barchet. 1993. *Episodic Acidification of Streams in the Northeastern United States: Chemical and Biological Results of the Episodic Response Project.* EPA/600/R-93/190. Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC.

ANC and pH below levels naturally expected during episodes.

- Fish in all three regions studied, exposed to low pH and high Al_{im} over longer periods of episodic exposure had higher short-term mortality rates and showed greater long-term adverse population-level effects. Time-weighted median Al_{im} concentration was the single best predictor of brook trout mortality found during these studies. Furthermore, it was concluded that stream assessments based solely on chemical measures during low flow do not accurately predict the status of fish communities in small streams.

- The ability of fish to avoid episodic acidic water conditions by moving to less affected waters only partially mitigated the adverse effects in small streams. Such behavioral adaptations were not sufficient to sustain fish density or biomass at the levels expected in the absence of acidic episodes.

- Brook trout density and biomass were not different between chronically acidic streams and streams with episodes where ANC decreased to less than 0 μeq/l. Differences did exist, however, between streams with higher ANC with and without episodes.

This last point supports the hypothesis that episodic acidification can be the primary cause of adverse effects to brook trout (and other ecological components) in acid-sensitive streams (i.e., ANC≤ 50 μeq/l). These episodic effects potentially equal those seen in chronically acidic streams (ANC≤ 0 μeq/l). Indeed, effects from severe episodic acidification (i.e., events leading to ANC≤0 μeq/l in surface waters) are likely the first source of biological damage to most aquatic populations and communities inhabiting waters that have become chronically acidified. The continuing adverse ecological effects from episodic events often blend with and become indistinguishable from all other effects accompanying chronic acidification.

The findings of this study and other analyses clearly point to the importance of considering potential effects of both long-term chronic and short-term episodic acidification when considering the effectiveness of an acid deposition standard or standards.

For most regions of North America at risk from acidic deposition, the effects from nitrogen deposition on aquatic systems are more likely to remain primarily episodic in nature, except when watersheds move toward nitrogen saturation, and nitrogen increasingly becomes a direct cause of both episodic and chronic acidification. Currently, data available for most regions are inadequate to extensively assess episodic effects related to nitrogen deposition or to assess the potential for and rate of watershed nitrogen saturation. Furthermore, while available data on episodic acidification may increase, because of the difficulty, expense, and often the risk involved in collecting data during episodic events (e.g., intensive spring sampling in high-elevation snowmelt areas), data bases for assessing episodic effects are not likely to become comprehensive. Clearly, both SO_4^{2-} and NO_3^- deposition can have major influences in surface water acidification processes. Evaluating the effectiveness of and options for acid deposition standards should include simultaneous consideration of both acidification causes.

2.2.3 Cumulative Loading Effects

Deposited sulfur and nitrogen can be incorporated into watersheds over the long term through a variety of physical, chemical, and biological processes. Current evidence suggests that the principal dynamic mechanism of concern with regard to watershed sulfur retention is physical/chemical in nature (i.e., adsorption of inorganic sulfate). On the other hand, the principal dynamic storage mechanism of nitrogen retention in watersheds appears to be biological in nature. Non-biological removal mechanisms also may incorporate some nitrogen into long-term storage within some watersheds, but this process is poorly understood.

Overall, the dynamics of sulfur adsorption and desorption and nitrogen retention over landscapes of different scales (watersheds to regions) can vary significantly. Considerable uncertainty exists in understanding these dynamics. Despite this uncertainty, available results strongly indicate that time is critical in defining sensitivities of resources to inputs of both sulfur and nitrogen. While most watersheds can assimilate considerable quantities of both chemicals without significant adverse effects, their assimilative capacities are finite. Watershed assimilative capacities vary with how rapidly deposited chemicals are assimilated and the time over which repeated deposition events impair these abilities. In other words, there are varying deposition frequencies, rates, and durations when

watershed assimilative capacities reach saturation. This is sometimes called *steady state,* the point when the output (loss) of a substance from a watershed (e.g., sulfur leaving a watershed in the form of SO_4^{2-} in stream flows) equals its input (e.g., as sulfur-containing compounds in deposition) on an annual basis.

Although sulfur deposition over the long term can lead to equilibrium or steady state in watersheds, similar steady-state conditions for nitrogen deposition are likely to be much less common. This is because nitrogen uptake dynamics are affected much more by biological changes within watersheds, such as forest cutting and regrowth as well as natural vegetative succession. Consequently, assessing the history of both sulfur and nitrogen deposition is important in assessing long-term effects attributable to cumulative loadings by acidic deposition.

A resource's or region's current sensitivity to acidic deposition, therefore, needs to be evaluated with respect to the historical deposition patterns and responses. Many regions with ample buffering capacity and remaining sulfur and nitrogen adsorption capacities may benefit little from future decreases in acidic deposition. Other regions facing imminent depletion of their buffering or adsorption capacities, however, would likely be highly responsive to decreasing deposition rates. The DDRP, discussed in Section 2.5.2, provides a useful beginning for understanding underlying relationships and defining remaining uncertainty about post-deposition dynamics of atmospheric sulfur deposition in watersheds within three regions of the eastern United States. The Nitrogen Bounding Study (NBS), discussed in Section 2.5.3, provides additional useful results to improve our understanding of the influence of nitrogen saturation on watershed processes affected by combined sulfur and nitrogen deposition within the three regions studied in the DDRP.

2.2.4 Recovery of Acidified Ecosystems

Acidified ecosystems can show signs of recovery following reductions in acidic deposition rates. Benefits have been demonstrated in (1) regions where major local source emissions have been reduced, (2) experimental aquatic and terrestrial systems where applied doses of acids have been reduced or ended, (3) limed watersheds and surface waters, and (4) model projections. Varying degrees of successful recovery in communities of microbes, algae, higher plants, invertebrates, fish, and amphibians were noted in the 1990 NAPAP studies.[11] Degrees of ecological recovery, however, did vary among the species, groups, and studies reviewed.

Recovery rates depend primarily on three factors: (1) rates of reduction in emissions and deposition of SO_4^{2-} and NO_3^-; (2) ongoing acid retention processes in terrestrial environments, including sulfate adsorption and base cation weathering; and (3) time lags caused by delayed biological process responses. In some instances, significant lags are involved or irreversible changes have occurred. The influence of such lags accompanying slow, gradual chemical improvements are well illustrated in a series of studies of Ontario lakes following reduced emissions from the Sudbury area smelters.[12]

Mitigation strategies that attempt to restore ecosystems without reducing deposition (e.g., liming) are only partially successful in restoring water quality and recovering biological populations. In fact, rarely will distressed ecosystems return to their predisturbance condition after the cause of the disturbance has been removed, because the complex ecological interrelationships among predisturbance species are rarely the same following disturbance of the system and its recovery. When natural evolutionary and successional regimes of predisturbed systems are disrupted, competition for nutrients and other habitat resources and predatory relationships among species in recovering systems have subtle to substantive differences from their predisturbance relationships. Thus, restoration to the "predisturbance condition" is not always possible, nor is it necessarily an appropriate goal.[13] Alternatively, rehabilitating or rejuvenating selected at-

[11] Baker, J.P., D.P. Bernard, S.W. Christensen, M.J. Sale, J. Freda, K. Heltcher, D. Marmorek, L. Rowe, P. Scanlon, G. Suter, W. Warren-Hicks, and P. Welbourn. 1990. *Biological Effects of Changes in Surface Water Acid-base Chemistry.* NAPAP Report 13. In: Volume II, National Acid Precipitation Assessment Program, Acidic Deposition: State of Science and Technology. Superintendent of Documents, Washington, DC.

[12] Keller, W., J.R. Piblado, and J. Carbone 1992. Chemical responses of acidic lakes in the Sudbury, Ontario area to reduced smelter emissions, 1981-1989. *Canadian Journal of Fisheries and Aquatic Sciences* 49 (Suppl. 1):25-32.

[13] Cairns, J., Jr. 1989. Restoring damaged ecosystems: Is predisturbance condition a viable option? *Environmental Professional* 11:152-159.

tributes or functions may be all that is required for restoration to be deemed successful.

A recent review and assessment concluded that uncertainty remains concerning the definition of appropriate measures of reversibility and recovery for acidified ecosystems.[14] Differences exist particularly between setting goals based on human-centered objectives (e.g., fish production for human use) versus more intangible ecological and conservation purposes. Further, assessment of ecosystem recovery following deposition reductions can be obscured by other environmental perturbations such as climate change and modified land-use practices.

2.3 CHARACTERIZING RESOURCES AT RISK FROM ACIDIC DEPOSITION

Relationships of resources to acidic deposition depend on two characteristics: resource sensitivity and acidic deposition exposure rates. Simultaneously considering regional distributions of both characteristics allows assessments of risk potentials produced by acidic deposition over discrete geographic regions. This approach helps to define regional needs for and effectiveness of acid deposition standards. In this process, *sensitivity* is an inherent attribute of an individual resource that increases its susceptibility to likely adverse effects due to acidic deposition. *Exposure* is determined by the deposition intensity, frequency, duration, and specific times that acidic deposition falls into an area. *Risk* is the probability that exposure to potentially hazardous environmental conditions produced by acidic deposition will exceed the tolerance level for a sensitive resource and cause an adverse effect. For any sensitive resource to be at high risk from any hazardous substance or environmental condition, it must have a high probability of being sufficiently exposed to the substance or condition, such that its inherent ability to tolerate the change will be exceeded and adverse effects will likely result. Because environmental resources have ranges of sensitivities and risks to potential effects caused by acidic deposition, resources having equivalent sensitivities can have different risk potentials for adverse effects depending on where they are located.

The next two subsections review in more detail the concepts of resource sensitivity and risk as they apply to acidic deposition. Understanding these concepts is essential for determining

- Locations containing sensitive resources at risk,
- Which sensitive resources may be the appropriate primary focus of protection,
- Appropriate environmental assessment indicators, and
- The extent of protection afforded.

2.3.1 Defining Sensitive Resources

There are different types of sensitivities to acidic deposition, and a resource can be insensitive to one effect while being sensitive to others. For example, a region with highly alkaline surface waters may saturate with nitrogen. This saturation could lead to no change in surface water acidity, but could lead to significant increases in eutrophication downstream. Consequently, the term *sensitive* can be imprecise and confusing. It can be used to describe different scales of resolution for different resource units (e.g., extent of landscape areas, water chemistry characteristics, or species groupings), and different degrees of resource sensitivities. Also, each use has different scientific and policy implications. Such differences affect each potential criterion used in determining acid deposition standards. Thus, when considering potential resource effects and risks, it is important to carefully define the specific ecosystem components within the region and specific concerns regarding the sensitivity being addressed.

An early NAS report indicated that lakes and streams with ANCs of 200 μeq/l or less are sensitive and subject to damage at moderate acidic deposition rates, whereas surface waters with ANCs of 40 μeq/l or less are critically sensitive to such effects.[15] Although ANC is an important response indicator of potential surface water sensitivity, it is not the only relevant response indicator of sensitivity. For example, the presence or absence of acid-sensitive fish, invertebrates, algae,

[14] Dise, N, W. Ahlf, G. Brahmer, B.J. Cosby, J. Fott, M. Hauhs, I. Juttner, K. Kreutzer, G.G. Raddum, and R.F. Wright. 1994. Group Report: Are Chemical and Biological Changes Reversible? Pages 275-381 in C.E.W. Steinberg and R.F. Wright (editors). *Acidification of Freshwater Ecosystems: Implications for the Future*. J. Wiley and Sons, New York, NY.

[15] National Academy of Sciences. 1983. *Acid Deposition: Atmospheric Processes in Eastern North America*. National Academy Press.

and higher plant species are other relevant indicators of potential sensitivity and acidification problems in lakes and streams. Further, knowing the ANC of surface or ground waters provides little indication of the actual sensitivity of neighboring terrestrial resources. For example, injury to red spruce foliage attributable to acidic deposition typically has little direct relationship to the ANC of neighboring soils or waters. Consequently, when there is a need to assess potential effects of acidic deposition on terrestrial resources or ecosystems, assessments should consider other parameters or indicators of sensitivity in addition to ANC.

Because numerous natural phenomena and processes influence the sensitivity and potential risk status of resources, interpretation and projection of receptor responses to acidification are difficult. Factors that should be carefully evaluated when assessing needs for acid deposition standards include naturally occurring organic acidic systems, annual and seasonal variabilities in precipitation, and related climatic variability. Land and resource use (e.g., changes in fishing pressure, point and nonpoint nutrient discharges, mining runoff, and other watershed activities) also potentially confound interpretation of acidification sensitivity and effects. The types of effects caused by many of these factors are summarized in Exhibit 2. The list, although incomplete, shows that a considerable matrix of factors interact to determine the potential sensitivity of individual surface waters, watersheds, and the natural resources they contain. These interactions cause differences in sensitivity and responses to acidic deposition among resources within individual watersheds and among adjacent watersheds. Many factors summarized in the exhibit are discussed in greater detail in subsequent sections.

Exhibit 2 also suggests a focus on potential acidic deposition effects linked to terrestrial soils and aquatic resources. Such a focus is not surprising, because most acidic deposition eventually flows through soils and into aquatic systems. Responses by these resources to acidic deposition are clear, well understood, and in many cases well documented. Therefore, most of the following discussion concentrates on concerns associated with environmental changes in soils, lakes, and streams. Wherever possible, however, discussion is punctuated with summaries and highlights of potential relationships of acidic deposition to other terrestrial resources.

Our accumulated knowledge indicates that sensitive resources can be defined over multiple ranges of temporal, geographic, geochemical, and biological categories and scales. Also, aquatic resources can be sensitive to episodic short-term acidification, chronic long-term acidification, or both. Fundamental factors and attributes associated with differences in sensitivity include:

- ANC of surface and ground waters;
- Supply of base cations from bedrock and soil particle weathering;
- Supply of base cations and buffering by soil solutions;
- Physical and chemical adsorption, desorption, and reduction of sulfate;
- Biological assimilation of nitrogen within watersheds; and
- Ability of sensitive resident organisms to modify physiological processes or behavior patterns or otherwise escape in response to habitat changes attributable to acidification.

Thus, although considering levels of ANC in assessing sensitive resources is important, considering the presence and possible implications of other indicators of potential sensitivity (including the occurrence of threatened and endangered species) is often equally important. Appropriate definitions of sensitivity may therefore vary with precise policy questions being asked. When the primary concern is protecting water quality in sensitive surface waters, ANC often can be a useful response indicator. If concern is broadened to include the sensitivity of all natural resources, the approach used to classify sensitivities also should be expanded.

In congressional discussions regarding the mandate for an acid deposition standard study, Congress followed the example of the NAS report noted above in distinguishing between resources that are "sensitive" and those that are "critically sensitive" to the effects of acidic deposition. Resource sensitivity occurs on a continuum. Consequently, rather than refining assessments in the following sections to distinguish among responses for subcategories of sensitive resources (i.e, sensitive versus critically sensitive), it is more valuable to assess the degree to which sensitive resources, in general, are exposed to different levels of risk from

EXHIBIT 2. PRINCIPAL WATERSHED AND SURFACE WATER CHARACTERISTICS THAT INFLUENCE RESOURCE SENSITIVITY TO ACIDIFICATION[a]

Category	Increased Sensitivity	Decreased Sensitivity
Bedrock geology	Resistant to weathering (metamorphic, igneous)	Easily weathered (sedimentary, calcite containing)
Soils:		
Buffering capacity	Lower potential	Higher potential
Depth	Shallower	Deeper
SO_4^{2-} adsorption	Lower potential	Higher potential
SO_4^{2-} reduction	Lower potential	Higher potential
NO_3^- retention	Lower potential	Higher potential
Topography	Steep-sloped	Shallow-sloped
Watershed to surface water area ratio	Lower	Higher
Lake flushing rate	Higher	Lower
Watershed vegetation and land use:		
Dominant vegetation	Coniferous	Deciduous
Cultural influence	Forested	Agriculture, municipal
Forest management	Reforestation	Deforestation
Water quality:		
Alkalinity/ANC	Lower (< 200 μeq/l)	Higher (> 200 μeq/l)
SO_4^{2-} reduction	Lower potential	Higher potential
Trophic status	Highly oligotrophic	Less oligotrophic to eutrophic
Humic substances	Lowest concentrations	Higher concentrations
Sphagnum moss	Present	Absent
Climate/meteorology:		
Precipitation	Higher	Lower
Snow accumulation	Higher	Lower
Growing season	Shorter	Longer
Alkaline dusts	Lower	Higher

[a] Modified from Marcus, M.D., B.R. Parkhurst, and F.E. Payne. 1983. *An Assessment of the Relationship among Acidifying Depositions, Surface Water Acidification, and Fish Populations in North America.* EA-3127, Volume 1, Final Report. Electric Power Research Institute, Palo Alto, CA.

acidic deposition across different geographic areas. As such, the term *critically sensitive* resource is not used in this report. Much of the following discussion does, however, focus on sensitivities and responses for surface waters projected by EPA model analyses for lakes and streams having ANCs of 50 μeq/l or less, a value that approximates the ANC value of 40 μeq/l considered by NAS and Congress to distinguish between their two sensitivity groupings of concern. Therefore, discussions in the following section regarding acidification relationships in lakes and streams with ANCs≤50 μeq/l can generally be interpreted as applying to "critically sensitive" resources.

2.3.2 Identifying Resources at Risk

Sensitivity, as noted above, is only one determinant of potential risk. For a resource to be at risk, it must be sensitive to a potential stressor and must have an actual or reasonable possibility of exposure to the stressor in a magnitude sufficient to cause an adverse effect.[16] Sensitive resources are at low risk when located where acidic deposition

[16] Risk Assessment Forum. 1992. *Framework for Ecological Risk Assessment.* EPA/630/R-92/001. U.S. Environmental Protection Agency, Washington, DC.

loads are currently below and are projected to remain below thresholds likely to cause adverse effects. For example, NAPAP studies reviewed in Appendix A generally indicate that many surface waters in western North America are likely to be more sensitive to adverse effects from acidic deposition than are similar resources in eastern North America. Because current deposition levels in the West are generally below thresholds that produce long-term surface water acidification, however, the present risk to these resources from chronic acidification is low. If the intensity of western deposition increases, adverse chronic acidification effects in the West might exceed those in the East. Consequently, the potential for high future risk to sensitive western resources remains a concern.

Risk assessment, therefore, must address not only whether a location now receives sufficient acidic deposition to produce adverse effects, but also the likelihood that the intensity and composition of the deposition may change in the future, thereby changing future exposure and potential risks to receptor resources. Consequently, it is necessary to determine what residual risks to sensitive resources remain after implementing emissions controls required by the CAAA, where these risks may be located, and their significance. For example, EPA modeling analyses indicate the degree to which sensitive resources will be protected when current Title IV requirements are fully implemented (i.e., emissions reductions of 10 million tons SO_2 and 2 million tons NO_x). But, how might sensitive resources benefit from further decreases in deposition rates or implementation of a deposition standard? How might these benefits change with varying additional reductions of sulfur or nitrogen deposition? How do possible changes in sulfur or nitrogen retention within watersheds affect these possible relationships? The DDRP and NBS, as discussed in Sections 2.5.2 and 2.5.3, begin to answer these questions.

Resources potentially sensitive to and at risk from acidic deposition occupy vast expanses of watersheds and forests, multitudes of lakes, and miles of streams in regions scattered across North America. A complete census of these resources would be prohibitively time consuming and costly. Instead, assessments of locations containing sensitive resources must depend on statistically based surveys, using proven methods to characterize populations within an estimated probability of error. Regional and resource priorities for an acid deposition standard or standards should be based on such surveys. Information summarized in Section 2.4 reviews survey results useful in targeting geographic regions at risk and identifying sensitive resources.

2.4 IDENTIFICATION OF RESOURCE AND REGIONAL PRIORITIES

2.4.1 United States

Scientific information from the extensive research efforts supported and reviewed by NAPAP directly apply to setting needs and priorities for protecting resources and regions sensitive to acidic deposition. Appendix A summarizes the major conclusions from 10 of NAPAP's State of Science and Technology reports. This section synthesizes general findings from these reports.[17] Also summarized here is additional information from more recent research regarding identification of regions sensitive to the effects of acidic deposition in the United States[18] and Canada.[19]

The NAPAP studies, which provide much of the best information currently available for the United States, contain clear implications for identifying resources most at risk from atmospheric deposition of acidic compounds. Of all effects to environmental resources from acidic deposition, the scientific community best understands changes in lakes, streams, rivers, and soil chemistries. The rate and extent of acidic deposition effects on other resources are less clear.

1. SOIL CHEMISTRY EFFECTS: In the eastern United States, concentrations of sulfur in soils generally follow trends in sulfur deposition. In some regions, soil concentrations of calcium and magnesium are inversely related to sulfur deposition loads resulting in soil nutrient depletion. Further, a recent study suggests that most calcium and magnesium in the soil of the spruce-fir ecosystem in the Northeast was lost 20–40 years

[17] This review is primarily drawn from conclusions presented by P.M. Irving (editor). 1991. *Acidic Deposition: State of the Science and Technology - Summary Report of the U.S. National Acid Precipitation Assessment Program.* National Acid Precipitation Assessment Program, Washington, DC.

[18] The primary source for this additional summary information is NAPAP. 1992. Report to Congress. National Acid Precipitation Assessment Program, Washington, DC.

[19] Brydges, T.G. 1991. Critical loads, reversibility and irreversibility of damage to ecosystems. Pages 245-260 in *Electricity and the Environment,* International Atomic Energy Agency, Vienna, Austria.

ago due to acidic deposition, when deposition rates were increasing rapidly. While control studies quantitatively link changes in soil chemistries to tree and other plant responses, similar studies linking acidic deposition effects on soils to actual plant effects in nature remain inconclusive.[20] Many important studies are continuing, however. The most apparent influence of soil chemistry responses attributable to acidic deposition are seen in effects on surface waters (see Item 3, below).

2. FOREST AND AGRICULTURE CROP EFFECTS: Developing evidence indicates that acidic cloud water, in combination with other stresses, likely increases winter injury, and reduces tree vigor and growth, and causes crown damage and death to high-elevation red spruce forests in the United States, particularly in the northern Appalachians and high-elevation regions of the Northeast. Evidence of acidic deposition involvement in the decline of red spruce in the southern Appalachians is less substantial. Involvement of acidic deposition in the decline of sugar maples in parts of the northeastern United States and eastern Canada has not been demonstrated but cannot be ruled out on the basis of available information. Recent information, in fact, indicates an apparent improvement in sugar maple tree health since 1988, with no visible effects from sulfate deposition, with the exception of observed decline in health of the Ontario maple.[21] The vast majority of forests in the United States and Canada have not declined. Within forested regions, acidic deposition primarily exerts its stress on nutrient cycling. Some evidence suggest that lichen communities and chemistries may be useful early indicators of forest health effects. Ambient acidic deposition levels have not been shown to be responsible for agricultural crop yield reductions.

3. SURFACE WATER ACIDIFICATION: Numerous lines of evidence support the fact that acidic deposition can acidify surface waters and that acidification attributable to acidic deposition has occurred in sensitive aquatic systems during this century (see Appendix A). Most sensitive lakes and streams in the United States—especially those that have current ANCs of 50 μeq/l or more—probably have not experienced recent chronic declines in pH or ANC associated with acidic deposition.

4. REGIONS CONTAINING SENSITIVE SURFACE WATERS: The National Surface Water Survey (NSWS) conducted under the auspices of NAPAP in 1984-85, identified six "high-interest areas" containing most of the surface waters surveyed (95 percent of the lakes and 84 percent of the stream reaches) that were chronically acidified as indicated by concentrations of inorganic anions, predominately SO_4^{2-}, NO_3^-, and Cl^-. These areas include the southwest Adirondack Mountains, New England, mid-Appalachian Region, Atlantic Coastal Plain, northern Florida Highlands, and low-silica lakes in the eastern Upper Midwest. Historical evidence supports the premise that acidic deposition undoubtedly is related to surface water acidification in the Adirondacks, the Pocono/Catskill subregion, mid-Appalachians, eastern portion of the Upper Midwest, the New Jersey Pine Barrens, and, to a lesser extent, the Florida panhandle. (Other areas of the Mid-Atlantic Coastal Plain appear to be affected more by organic acidification and land-use activities such as acid mine drainage.) Chronic acidification of western lakes from acidic deposition appears not to have occurred. The following subsections further describe several of the regions containing sensitive surface waters.

5. CHARACTERISTICS OF WATERSHEDS CONTAINING SENSITIVE SURFACE WATERS: Surface waters most sensitive to acidic deposition are often located in watersheds having shallow acidic soils with rapid, shallow subsurface flows. Acidic lakes and streams tend to occur in smaller watersheds and, in regions where significant elevation gradients exist, at the higher elevations (e.g., watersheds less than 30 km^2 and elevations greater than 300 m in the mid-Appalachian

[20] Brandt, C.J. 1994. *Acidic Deposition and Forest Soils: Potential Changes in Nutrient Cycles and Effects on Tree Growth.* Report to Watershed Response Program, Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, OR.

[21] U.S. EPA. 1994. *U.S. Canada Air Quality Agreement Progress Report.*

region and the Pocono/Catskill subregion). It must be noted, however, that these relationships are derived from studies emphasizing watershed responses to sulfate deposition. Other, primarily biological, relationships exist where deposition of acidifying nitrogen compounds are a significant or predominant concern.

6. RESPONSES BY SENSITIVE AQUATIC SPECIES AND ECOSYSTEMS: Acid-sensitive species occur in all major groups of aquatic organisms, but most is known about responses by fish and aquatic invertebrates. In general, sensitive aquatic species inhabiting surface waters that have low calcium concentrations (<100–150 μeq/l) begin to be affected by acidification processes as pH decreases below about 6.0–6.5 (Exhibit 3) and as inorganic monomeric aluminum concentrations increase above 30–50 μg/l. These changes affect these species first by decreasing their ability to survive, reproduce, or compete in acidic surface waters. Such responses can eliminate affected species and reduce species richness (i.e., the number of species living within a surface water). Such changes typically occur first in affected surface waters during episodic runoff events (i.e., when storm water or snowmelt runoff causes short-term flushes of acutely toxic water chemistries to enter receiving waters). System-level processes such as composition, nutrient cycling, oxygen usage, and photosynthetic rate are fairly robust and are affected only at relatively high levels of acidity (e.g., chronic pH less than 5.0–5.5).[22]

These findings lead to several working conclusions regarding sensitive resources and regions at potentially greatest risk from acidification, and the maximum degree of protection that may be necessary. It is on these resources, regions, and protection goals that considerations should focus regarding potential necessity and benefits of acid deposition standards:

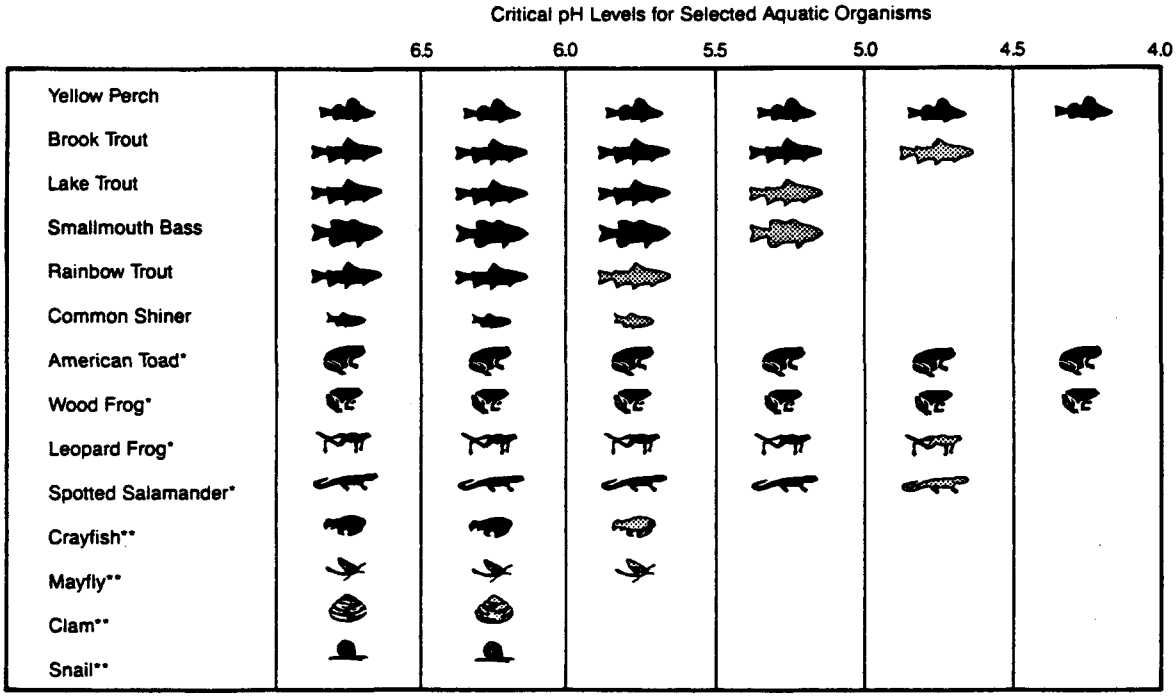
1. SENSITIVE RESOURCES OF PRIMARY CONCERN: Considering that the natural resources most sensitive to acidic deposition would exhibit the strongest responses and provide the most conclusive evidence of effects, it is reasonable to conclude that the natural resources most sensitive to acidic deposition are aquatic systems and high-elevation red spruce forests. Therefore, possible future acid deposition standards focused on protecting sensitive aquatic resources in the eastern United States and red spruce forests in the northern Appalachians and high-elevation regions of the Northeast should provide adequate protection for most sensitive natural resources at risk. Protection of sensitive aquatic resources should particularly focus on lakes and streams located where watersheds are smaller, have shallow acidic soils with rapid, shallow subsurface flows, and are at higher elevations.

2. REGIONAL PRIORITIES FOR PROTECTION: In the eastern United States, the 1990 CAAA and any future acidic deposition controls are most likely to reduce the threats of acidic deposition to surface water resources in these regions: Adirondack Mountains, Pocono and Catskill Mountains, mid-Appalachian Region, the Southern Blue Ridge Province, New Jersey Pine Barrens, northern Wisconsin and Michigan's Upper Peninsula, and, possibly, northern Florida. The first three regions apparently are now at continuing risk from acidification effects. Other regions with sensitive resources should be monitored and assessed to evaluate whether continuing acidic deposition will affect those resources. These areas include parts of Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island; northern Minnesota; parts of the Ozark Mountains, Ouachitas Mountains, the Carolina Piedmont, and the Atlantic Coastal Plain; and parts of the Rocky Mountains, Sierra Nevada Mountains, and Cascade Mountains.

3. PROTECTION GOALS FOR AQUATIC SPECIES: The biological effects of inorganic monomeric aluminum associated with acidic deposition are minimized as the level of acidic deposition is decreased and pH and ANC levels in sensitive waters are kept relatively high. Based on studies of sensitive aquatic species, to protect aquatic resources in sensitive watersheds from the effects of long-term, chronic acidification, a general

[22] Schindler, D.W. 1987. Detecting Ecosystem Responses to Anthropogenic Stress. *Canadian Journal of Fisheries and Aquatic Sciences* 44(Suppl.):6-25.

EXHIBIT 3. CRITICAL pH FOR SELECTED TAXA IN LAKES AND STREAMS[a,b]



[a] From National Acid Precipitation Assessment Program. 1991. *1990 Integrated Assessment Report.* NAPAP Office of the Director, Washington, DC.

[b] Solid symbols for each type of organism are placed in favorable pH ranges; shaded symbols are placed in less favorable ranges. No symbol is placed in pH ranges that generally do not support populations of a particular type of organism.

* Embryonic life stages.

** Selected species.

goal is to maintain the pH of sensitive lakes above pH 6.0-6.5 and inorganic monomeric aluminum below 30-50 µg/l. To protect these resources from the potential effects of episodic, acute acidification, surface water ANC should be maintained at or above 50 µeq/l. No single water quality goal, however, addresses all needs to protect sensitive surface water resources. Goals to protect aquatic resources may also address site-specific needs to maintain sensitive aquatic species, species of special concern (e.g., listed threatened or endangered species), and species richness in these sensitive surface waters. This effort certainly must include recognition that pH levels less than 6.0 and ANC less than 50 µeq/l occur in some naturally acidic surface waters, and that levels of pH less than 6.0 can occur naturally in some locations accompanying periods of episodic stormwater and snowmelt runoff. The specific environmental objectives of any acid deposition standard should accommodate the ranges of chemical qualities occurring in natural waters. Furthermore, they should protect those special biological communities evolved to inhabit naturally acidic surface waters.

2.4.2 Identification of Sensitive Aquatic Resources in Other North American Regions

Most of this chapter reports quantitative results based on EPA model analyses for three case study regions: the Northeast (including the Adirondack Mountains), the mid-Appalachian Region, and the Southern Blue Ridge Province. Similar model analyses were not performed for other sensitive regions of North America due to data and budget limitations. Instead, and in addition to the results of the NAPAP National Surface Water Survey, EPA supported a recent report that reviewed the re-

sponses of aquatic resources to acidic deposition in four other regions of North America identified in previous studies as holding sensitive aquatic resources: the mountainous western United States, upper midwestern United States, and northern Florida.[23] That review addressed effects from acidic deposition, specifically sensitive aquatic resources in each region. The approach incorporated key results available from past research and assessment efforts in North America and Europe. The major conclusions derived during this review that specifically related to the four regions assessed are presented below. (Some conclusions from this review regarding general deposition and response relationships duplicate the findings of other studies reported above and are not repeated in this section.)

Western United States

- Most low-ANC lakes in the West are confined primarily to glaciated, higher elevation, mountainous regions. These waterbodies can be generally consolidated into five lake populations, based on their locations within similar geomorphic units: (1) the Sierra Nevada in California; (2) the Cascade Mountains in California, Oregon, and Washington; (3) the Idaho Batholith in Idaho and Montana; (4) the mountain ranges of northwestern Wyoming; and (5) the Rocky Mountains in Colorado.

- Results of the NSWS indicate that although no lakes in this region are chronically acidic, many lakes were found to have very low ANC (i.e., 17 percent have ANC≤ 50 μeq/l), and should be considered susceptible to acidification, particularly episodic acidification.

- Watersheds in the alpine areas of these five regions generally include broad expanses of exposed bedrock, which is often highly resistant to weathering, and contain little soil or vegetative cover to neutralize acidic inputs. Consequently, these regions include a significant portion of the region's aquatic resources that are the most sensitive to acidic deposition.

- Natural characteristics of these watersheds particularly predispose the surface waters they contain to episodic acidification effects: (1) low-water retention capacities of most watersheds; (2) ultra-low concentrations of base cations; (3) low ANC in surface waters throughout the year; (4) large snowpack accumulations and substantial base cation dilution during runoff; (5) frequent, periodic, heavy rain storms with high runoff events; and (6) short water retention times and high flushing rates for most lake basins.

- Nitrate concentrations in the majority of the western lakes are virtually undetectable during the fall. The NSWS samples, however, revealed that a relatively large number of lakes in northwestern Wyoming, Sierra Nevada, and Colorado Rockies contained high concentrations of NO_3^-. These concentrations were sufficiently high to indicate that many watersheds in these regions may have little remaining capacity to assimilate excess NO_3^- deposition.

- No extant data suggest that lakes in the West have experienced chronic acidification. It is likely, however, that episodic effects have occurred in some lakes under some current deposition regimes and that deposition concentrations of NO_3^- especially have caused small, chronic losses of ANC in some high-elevation watersheds. As previously described, both nitrogen and sulfur have the potential to contribute to episodic acidification.

- Fish population data, although very limited, do not indicate a significant effect due to acidification. However, trout species native to Western lakes such as rainbow trout and cutthroat trout are considered more sensitive to low pH and elevated aluminum than brook trout native to eastern lakes and streams.

- Although potentially difficult based on wide ranges in precipitation volume, an event-based deposition standard may be a consideration to adequately address the potential effects of episodic acidification in the West. Another consideration which combines concerns for both total mass and

[23] Sullivan, T.J., and J.M. Eilers. 1994. *Assessment of Deposition Levels of Sulfur and Nitrogen Required to Protect Aquatic Resources in Selected Sensitive Regions of North America.* Final Report. Environmental Research Laboratory-Corvallis, U.S. Environmental Protection Agency, Corvallis, OR.

maximum concentration of pollutants deposited, is an acid deposition standard which establishes limits based on the maximum allowable annual-weighted pollutant concentrations or based on total annually deposited chemical mass loading.

Upper Midwestern United States

- The Upper Midwest is characterized by numerous lakes created by repeated glaciation, little topographic relief, deep glacial overburden, and rarely exposed bedrock. In this region the primary aquatic resources sensitive to acidic deposition are seepage lakes with low base cation concentrations that receive nearly all of their water inputs as precipitation directly onto the lake surface. These lakes have generally long water retention times, which provide opportunities for in-lake SO_4^{2-} reduction and NO_3^- assimilation processes to neutralize most acidic inputs and to prevent the concentration of SO_4^{2-} through evaporation.

- The Upper Midwest has a large population of low-ANC lakes, but relatively few acidic (ANC≤0 μeq/l) lakes. Paleolimnological evidence suggests that some of these lakes, particularly in Michigan's Upper Peninsula, have developed low ANC or become acidic, consistent with historic trends for sulfur deposition since preindustrial times. It should be noted that land use changes and other human disturbances in the watersheds have exerted greater influences on the acid-base chemistry in more sensitive lakes of this region than has acidic deposition.[24]

- The NSWS indicated that 19 percent of the lakes in this region have ANC≤50 μeq/l (only 3 percent of that figure is ANC≤0). Historical data are too limited to determine the degree to which acidic deposition has impacted fish populations in this region such as yellow perch, bass, and others. However, lakes with low pH in northeastern Wisconsin and upper Michigan support fewer fish species than expected for their size and lake type.

- Concentrations of inorganic nitrogen are uniformly low in surface waters throughout this region. Most nitrogen is efficiently retained by terrestrial and aquatic organisms. Snowmelt has not been shown to provide any significant influx of NO_3^- to these lakes because most snowmelt water percolates through the soil prior to entering surface waters, allowing terrestrial organisms to assimilate the deposited nitrogen. Therefore, the key concern for this region is chronic, sulfur-driven acidification. If recent trends of decreasing sulfur deposition in the Upper Midwest were to reverse, lakes with ANCs near zero in this region could be expected to acidify.

Northern Florida

- Florida lakes are located on marine sands overlying carbonate bedrock; where groundwater interacts with the deeper aquifer, surface water can be highly alkaline. Lakes that receive input waters only from shallow aquifers in highly weathered sands, however, can be quite acidic and sensitive to acidic deposition. In fact, northern Florida contains one of the largest populations of acidic lakes in the United States. Seventy-five percent of the Panhandle lakes are acidic, as are 26 percent of the lakes in the northern peninsula.

- The NSWS determined that approximately 60 percent of the acidic lakes in Florida, primarily in the northcentral peninsula, are acidic due to acidic deposition. Subsequent scientific study however, suggest that the role of the natural sulfate bearing ground water, significant land use changes in the region, and marine sources likely have greater effects on the acidic water chemistries of these systems than was previously estimated. Therefore, the extent of possible water quality changes due to acidic deposition alone in Florida cannot now be quantified, but is likely lower than the NSWS estimate. The best evidence that acidic deposition effects have altered the surface water chemistry exists for the Trail Ridge region in northeastern Florida. Available data currently indicate that there has been no widespread biological damage

[24] Sullivan, T.J. 1990. *Historical Changes in Surface Water Acid-Base Chemistry in Response to Acidic Deposition.* SOS/T 11, National Acid Precipitation Assessment Program, Washington, DC. 212 pp.

due to acidic deposition within the sensitive regions studies in northern Florida.

2.4.3 Canada

The area of Canada considered to be at greatest risk from acidification (i.e., the region having minimal ability to neutralize incoming acids and receiving elevated deposition of potentially acid-forming chemicals), includes the region east of the Manitoba-Ontario border and roughly south of 52° N latitude (near the southern limit of James Bay).[25] (Known threats to forests in this regions, as summarized by NAPAP, were reviewed earlier in this section.) This area contains more than 700,000 lakes covering about 160,000 km^2 (excluding the Great Lakes). Extrapolation of survey information indicates that 14,000 lakes are presently acidic. Modeling projections for eastern Canada indicate that at least an additional 10,000 to 40,000 lakes would become chronically acidic at 1985 deposition levels, as watershed input-output budgets reach equilibrium over time with concentrations of atmospherically deposited acid-forming ions.

Four important relationships primarily influence the surface water chemistry of these Canadian lakes and their potential sensitivity to acidification:

1. Because of the predominance of silicate bedrock, thin overburden, and generally high precipitation volumes (approximately 100 cm/yr or greater), nearly all lakes in eastern Canada can be hydrologically characterized as drainage lakes.[26] (The acidification processes that dominate seepage lakes in the upper Midwest and Florida lack importance in most Canadian lakes.)

2. Most glacially deposited soil covering eastern Canada has essentially no capacity for SO_4^{2-} adsorption. Because there appears to be no significant geological sources of SO_4^{2-} in this region, limited adsorption capacity indicates that existing SO_4^{2-} levels are principally controlled by atmospheric inputs. Note that most glacially deposited soil covering eastern Canada is similar to the soils in the northeast United States (i.e., Adirondacks) in that they have very limited SO_4^{2-} adsorption capacity, and acidification is primarily controlled by atmospheric inputs in both regions. [27]

3. Base cation production of principally Ca^{2+} and Mg^{2+} by primary weathering or cation exchange in the surrounding terrestrial watershed provide most of the ANC of all Canadian lakes. Thus, the variable mineralogy in glacial overburden surrounding the lakes dominates control of subregional variability in sensitivity to acidification.

4. Organic acid anions appear to be important in some waters, particularly in the extensive wetland areas of Nova Scotia, Newfoundland, Labrador, and northwestern Ontario; the occurrence of these anions, however, are generally not the primary cause of acidity in all lakes with ANC of 0 μeq/l or less and pH less than 6.0.

Almost all known acidification related losses of lake trout *(Salvelinus fontinalis),* smallmouth bass *(Micropterus dolomieui),* and walleye *(Stizostedion vitreum)* in Ontario surface waters have occurred in the Sudbury area and are related to emissions from the Sudbury area smelters; complete or biologically significant reversal of acidic conditions in these waters, however, may depend on continued reductions in emissions over a wider region.[28] Concern also continues regarding probable episodic influence of acidic deposition on Atlantic salmon in tributary streams along the Atlantic coast from Maine northward.[29]

---

[25] Information presented in this section regarding sensitive aquatic resources in Canada, unless otherwise cited, comes from the summary of Jefferies, D.S. 1991. *Southeastern Canada: An Overview of the Effects of Acidic Deposition on Aquatic Resources.* Pages 273-286 in D.F. Charles (editor). Acidic Deposition and Aquatic Ecosystems - Regional Case Studies. Springer-Verlag, New York, NY.

[26] *Drainage lakes* are lakes with permanent surface water inlets and, usually, outlets. *Seepage lakes* are lakes with no permanent surface water inlets or outlets.

[27] Sullivan, T.J. 1990. *Historical Changes in Surface Water Acid-Base Chemistry in Response to Acidic Deposition. SOS/T* 11, National Acid Precipitation Assessment Program, Washington, DC. 212 pp.

[28] Keller, W. 1992. Introduction and overview to aquatic acidification studies in the Sudbury, Ontario, Canada, area. *Canadian Journal of Fisheries and Aquatic Sciences* 49(Suppl. 1):3-7.

[29] Lacroix, G.L. 1989. Ecological and physiological responses of Atlantic salmon in acidic organic rivers of Nova Scotia, Canada. *Water, Air, and Soil Pollution* 46:375-386.

2.5 ASSESSING PROTECTION NEEDS AND RESOURCE RESPONSES IN THE CONTROL OF ACIDIC DEPOSITION

Determining the potential for future benefits from additional control of acidic deposition involves assessing changes over broad geographical and ecological scales. Projecting potential future relationships is best done using models to simulate possible future scenarios. Simulation models are, in fact, conceptualizations of the way things "work." Due to the very simple character of their controlling process, some models can be very precise and can be verified repeatedly by comparisons of projections to subsequent observations (e.g., projections of solar eclipses). In contrast, models of watersheds and of surface water responses to environmental perturbations (e.g., acidic deposition) are much more difficult to design and test.

This section briefly reviews the use and constraints of simulation models. It presents detailed results from two major EPA modeling studies and an extensive literature review aimed at increasing the understanding of how acid-sensitive soil and aquatic resources are affected by both sulfur and nitrogen deposition. International and state effects-based efforts to regulate acidic deposition are also described. Findings from a recent EPA investigation, previously described in Section 2.2.2, show the key involvement of rainstorm and snowmelt events in lake and stream acidification and are summarized here as well.

2.5.1 Model Application

MAGIC (Model for Acidification of Groundwater in Catchments) is currently the model of choice for assessing many watershed processes associated with acidic deposition (Exhibit 4). It provided the primary analytical basis for EPA's DDRP and the NBS, as summarized in the next two subsections. MAGIC has been tested more than any other acidic deposition effects model. Results from these tests (including some still underway) indicate that MAGIC correctly projects the direction of change of watershed responses and accurately projects the magnitudes of rates of change for surface water ANC and pH. MAGIC reasonably represents sulfur retention within watersheds and the generation and leaching of cations from watersheds, two functions generally acknowledged to be the most important of the modeled processes.

In recognizing that all models have strengths and weaknesses, it is obviously unreasonable to expect that MAGIC (or any other watershed acidification model) will predict accurately exact values of ANC or pH for any individual lake or stream in the distant future (e.g., 50 years or more) under conditions of significant dynamic change. Rather, the appropriate use of MAGIC and other such models is to project the *direction* and *magnitude* of possible chemical changes and to compare the *relative* potential effects of different scenarios of acidic deposition. MAGIC appears to be reasonably well suited for such tasks. In reviewing model projections from these two studies on potential effects attributable to future sulfur and nitrogen deposition, it remains important to keep in mind the associated uncertainties that are highlighted in the following sections.

2.5.2 Direct/Delayed Response Project

As introduced in Section 2.2.1, a 1984 NAS panel identified two geochemical processes as the dominant watershed factors affecting or mediating long-term surface water acidification: (1) the rates at which a watershed supplies base cations through neutralization and buffering processes in response to its assimilation of deposited acids, and (2) the capacity of a watershed to retain deposited sulfur-containing compounds. (This NAS report included minimum concern regarding effects from nitrogen deposition). The capabilities of watersheds to perform these processes decrease over time. Consequently, based largely on the NAS conclusions, defining needs to protect various aquatic and terrestrial resources from acidic deposition depended on whether acidification is immediately proportional to the intensity of the deposition (i.e., "direct") or lags in time (i.e., "delayed") through such watershed processes.

The DDRP was designed to begin assessing the state and influence of these processes. The mandate of the DDRP was to make comparative regional projections of the future effects of sulfur deposition on long-term surface water chemistry in the eastern United States, based on the best available data and most widely accepted hypotheses of the acidification process related to atmospheric deposition.

Two principal reports produced by the DDRP assessed potential long-term effects of sulfur deposition on lake and stream water chemistry in the eastern United States. The first report focused on analysis of lake resources in the Northeast and stream resources in the Southern Blue Ridge Prov-

EXHIBIT 4. MAGIC

MAGIC is a lumped parameter model of intermediate complexity that was originally developed to project long-term effects (i.e., decades to centuries) caused by acid deposition on surface water chemistry. The model uses a minimum number of critical chemical and hydrological processes in watersheds to simulate soil solution and surface water chemistry, and to project average monthly or annual concentrations of acid-base chemistry in surface water. MAGIC was introduced in a pair of 1985 articles by B.J. Cosby, G.M. Hornberger, J.N. Galloway, and R.F. Wright:

- Time scales of catchment acidification: A quantitative model for estimating freshwater acidification. *Environmental Science and Technology* 19:1144-1149; and
- Modeling the effects of acid deposition: Assessment of a lumped parameter model of soil water and stream water chemistry. *Water Resources Research* 21:51-63.

Church et al. (see footnote 30) summarize various studies using MAGIC. Recent modifications of the model are summarized by Sullivan, T.J., B.J. Cosby, C.T. Driscoll, H.F. Hemond, D.F. Charles, S.A. Norton, and J.M. Eilers (1993. The influence of naturally occurring organic acids on model estimates of lake water acidification using the Model of Acidification of Groundwater in Catchments (MAGIC). Report DOE/ER/30196-3. U.S. Department of Energy, Washington, DC).

MAGIC has been tested more than any other acidic deposition effects model. Those tests indicate that its projections are reasonably reliable:

- Individual process formulations in the model have been tested against laboratory experiments with soils.
- Model hindcasts (i.e., backward predictions) of historical lake chemistries in the Adirondacks have been made and compared with values inferred from lake sediment records.
- Numerous predictions of the effects from whole-watershed manipulations have been compared to observed effects.

The MAGIC model, as all models, illustrates problems associated with uncertainty, parameterization, and validation. For example, MAGIC currently does not explicitly represent detailed cycling or processes affecting the rate of nitrogen uptake and release. In fact, processes (and their governing factors) that control the transition of a watershed to a state of nitrogen saturation are poorly known and, as yet, not represented in any complete or tested watershed model. Better nitrogen models to address the questions are being developed, however. The Nitrogen Bounding Study developed for this report used a series of four scenarios for time-to-nitrogen-saturation to "bound" the possibilities. The NBS represents the first time a nitrogen component has been added and effectively used with the MAGIC model for assessments at regional scales.

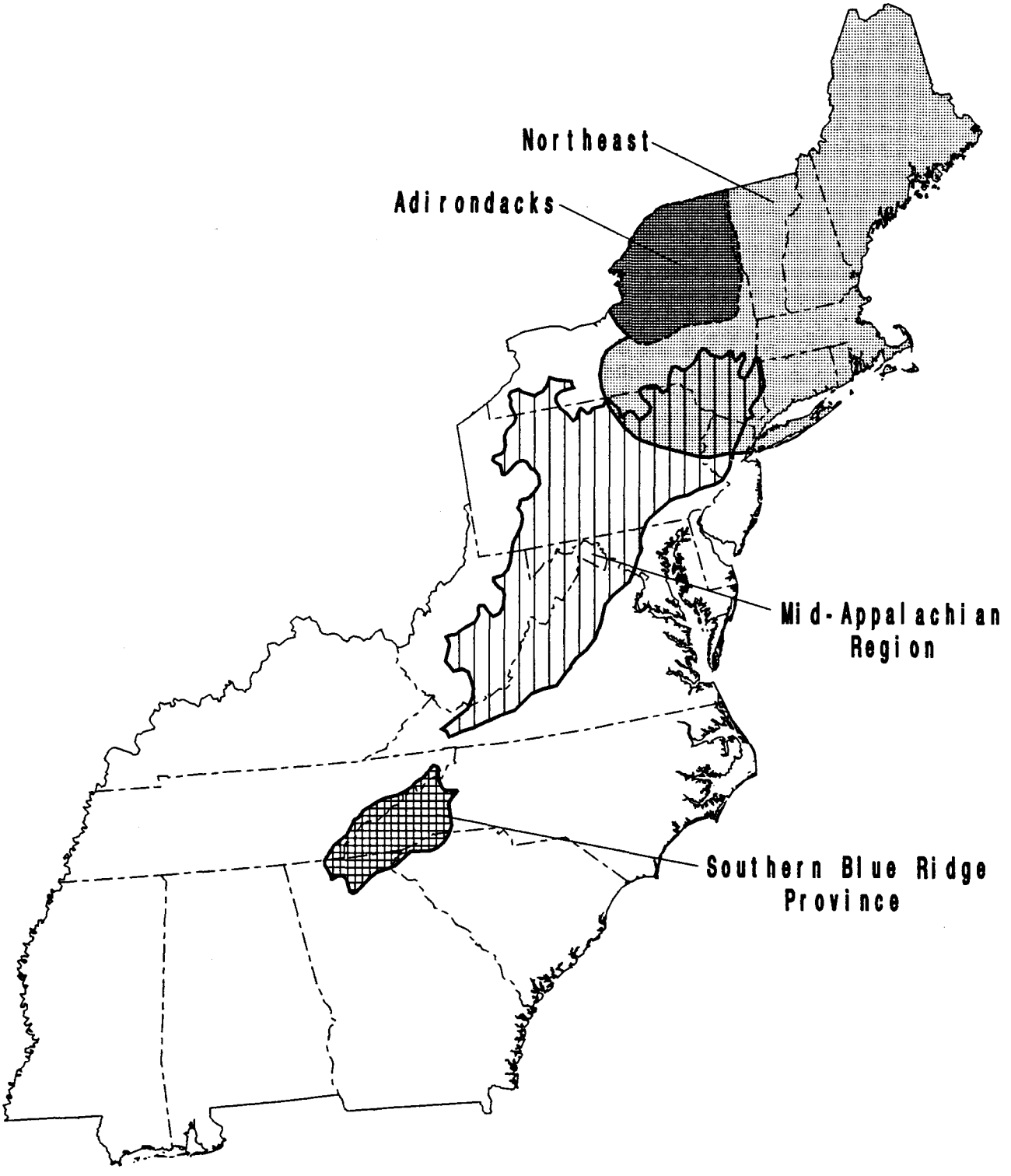
In analyses completed for the DDRP and the NBS, it is impossible to know precisely what deposition levels will be over the next 50 years or more. Therefore, the NBS approach assessed a range of deposition levels to evaluate potential effects of possible sulfur and nitrogen deposition combinations. This approach indicates why model runs are more correctly termed "projections" rather than "predictions." The latter implies an exact knowledge of model inputs and system dynamics. The NBS *projects* watershed acidification responses for possible alternative acidic deposition rates in the year 2040.

ince (SBRP).[30] The second report addressed potential stream chemistry effects in the mid-Appalachian Region, and summarized and integrated conclusions from the three regional analyses.[31] Exhibit 5 shows the locations of three study regions. General characteristics and sizes of target

[30] Church, M.R., K.W. Thornton, P.W. Shaffer, D.L. Stevens, B.P. Rochelle, G.R. Holdren, M.G. Johnson, J.J. Lee, R.S. Turner, D.L. Cassell, D.A. Lammers, W.G. Campbell, C.I. Liff, C.C. Brandt, L.H. Liegel, G.D. Bishop, D.C. Mortenson, S.M. Pierson, and D.D. Schmoyer. 1989. *Direct/Delayed Response Project: Future Effects of Long-term Sulfur Deposition on Surface Water Chemistry in the Northeast and Southern Blue Ridge Province.* EPA/600/3-89/026a-d. U.S. Environmental Protection Agency, Washington, DC. 887 pp.

[31] Church, M.R., P.W. Shaffer, K.W. Thornton, D.L. Cassell, C.I. Liff, M.G. Johnson, D.A. Lammers, J.J. Lee, G.R. Holdren, J.S. Kern, L.H. Liegel, S.M. Pierson, D.L. Stevens, B.P. Rochelle, and R.S. Turner. 1992. *Direct/Delayed Response Project: Future Effects of Long-term Sulfur Deposition on Stream Chemistry in the Mid-Appalachian Region of the Eastern United States.* EPA/600/R-92/186. U.S. Environmental Protection Agency, Washington, DC. 384 pp.

EXHIBIT 5. STUDY REGIONS INCLUDED IN THE DIRECT/DELAYED RESPONSE PROJECT AND THE NITROGEN BOUNDING STUDY



surface water populations for all regions included as part of the NSWS and the DDRP and NBS studies are presented for comparison in Exhibit 6. Specific characteristics of the three DDRP study areas and their surface waters are summarized in the following.

Northeast[32]

This region includes lakes potentially sensitive to acidic deposition over the near- to long-term and covers an area extending from northeast Pennsylvania and northern New Jersey through the entire State of Maine (Exhibit 5). Bedrock and surface physiographic characteristics in these subregions help to limit supplies of base cations draining from these glaciated and predominately forested watersheds. Seepage lakes are uncommon, representing only 7 percent of the lakes classified by hydrologic type, but seepage lakes also generally had the lowest values of ANC and pH of any lake type in this region. Although the NSWS included lakes with areas only between 4 and 2,000 ha (see Exhibit 6), there may be from one to four times as many lakes with areas less than 4 ha in the Northeast. Because of their smaller sizes and higher rates of water turnover, such lakes are likely to be more highly susceptible to acidic deposition effects. Concentrations of nutrients (i.e., NO_3^-, NH_4^+, and PO_4^{3+}) were low for most of lakes sampled in this region.

This region includes the highest dissolved concentration of SO_4^{2-} observed during the NSWS. Acidic lakes were also characterized by high concentrations of extractable aluminum.

The Adirondack subregion, including Adirondack State Park, which was emphasized during the NBS (see Section 2.5.3), has the highest number and percentage of acidic (ANC≤0 μeq/l) lakes (14 percent) found for any NSWS subregion, except Florida. Approximately half of the Adirondack lakes having pH 5.0 were organic acid dark-water lakes, while the remainder were clear water acid lakes. This indicates that inorganic ions, including mineral acids, were likely the primary cause of their acidity. Both pH and ANC tended to decrease as the lake elevation increased, a relationship not observed in other NSWS subregions of the Northeast. Drainage lakes were the most common type of lake (77 percent of the target population). Most lakes with areas of less than 4 ha in the Adirondacks are more boglike and more strongly influenced by organic acidity, compared to the larger lakes in this subregion.

Mid-Appalachian Region[33]

This region included most stream reaches potentially sensitive to acidic deposition within the area from central and eastern Pennsylvania through western Maryland and Virginia and into eastern West Virginia (Exhibit 5). This DDRP study region included the mountainous physiographic provinces of the Mid-Atlantic Appalachian Mountains, including the northern Blue Ridge Mountains, Valley and Ridge Province, and Appalachian Plateau. This area includes Shenandoah National Park in Virginia. Much of the area extends over bedrock that is relatively resistant to weathering. Rates of sulfur deposition in the mid-Appalachians are much greater than in the Northeast or SBRP.

Based on the National Stream Survey (NSS) streams acidified by acidic deposition (ANC≤0 μeq/l) accounted for 4 percent of the target stream length in this region; 18 percent of the upstream ends and 7 percent of the downstream ends had ANC≤50 μeq/l. These estimates excluded streams acidified by mine drainage (e.g., coal mining). Mine drainage was responsible for acidifying four times as many downstream reaches as acidic deposition.

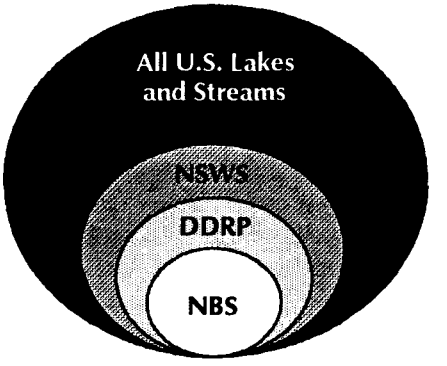
More than 99 percent of the acidic target streams (ANC≤0 μeq/l) within the mid-Appalachians were located in watersheds with at least 85 percent forest cover. Many more streams with very low ANC (≤50 μeq/l) are found in these forested areas, compared to those in mixed forest or open areas. This situation probably is not due to the fact that forests control ANC and acidic levels; rather, most remaining forested areas that were never clear cut lie in the less-weatherable, less-fertile uplands unsuitable for agriculture. Areas where forests were

[32] This summary is primarily drawn from Linthurst, R.A., D.H. Landers, J.M. Eilers, D.F. Brakke, W.S. Overton, E.P. Meier, and R.E. Crowe. 1986. *Characteristics of Lakes in the Eastern United States, Volume I: Population Descriptions and Physico-Chemical Relationships.* EPA/600/4-86/007a. U.S. Environmental Protection Agency, Las Vegas, NV.

[33] This summary is primarily drawn from Herlihy, A.T., P.R. Kaufmann, M.R. Church, P.J. Wigington, Jr., J.R. Webb, and M.J. Sale. 1993. The effects of acidic deposition on Streams in the Appalachian Mountain and Piedmont Regions of the Mid-Atlantic United States. Water Resources Research 29(8):2687-2703.

EXHIBIT 6. TARGET POPULATIONS INCLUDED IN THE NSWS, DDRP, AND NBS STUDIES

Target population refers to the number of systems for which model projections can be reasonably extrapolated. Studied target populations of surface waters generally became refined and smaller in each of these successive studies, allowing acidic deposition research efforts to focus increasingly on relationships in more sensitive surface waters (see figure—not drawn to scale). As a consequence of narrowing research efforts, proportions of sensitive surface waters and the magnitude of the potential response to acidic deposition by these respective target populations tend to increase through subsequent studies. General characteristics of these target populations are presented below.



As part of the NSWS, the Eastern Lake Survey (ELS) includes lakes between 4 ha (10 acres) and 2,000 ha (5,000 acres) in size that have ANC≤400 μeq/l, excluding non-freshwater lakes (i.e., small ocean bays and estuaries); broad waters with apparent flows (reservoirs were included, however); marshes or swamps; and waterbodies surrounded by urban, industrial, or agricultural activities (i.e., lakes with extensive cultural disturbance in their watersheds). In turn, the National Stream Survey (NSS) included target stream reaches in sensitive regions not sampled during the National Lake Survey (NLS) that had drainage areas <155 km^2 (<60 mi^2) and showed as "blue line" streams on 1:250,000-scale U.S. Geological Survey topographic maps. Such streams were judged to be large enough to be important for fish habitat, yet small enough to be susceptible to potential effects of acidic deposition. At least 50 percent of the stream reach had to be within the designated region to be included. Among the stream reaches excluded from the target population were, for example, reaches affected by gross pollution (e.g., mine or oil-field drainage), highly urbanized development, or tidal influence.

DDRP target lakes in the Northeast included a subset of NLS target lakes by excluding lakes <1.5 m deep. DDRP target stream reaches included a subset of the NSS target reaches by excluding streams with ANC>200 μeq/l in the mid-Appalachian region (Southern Blue Ridge Province streams had no additional restriction on ANC); drainage areas >3,000 ha (>7,400 acres); and all watersheds in the Southern Piedmont Regions and Coastal Plain and north of the maximum extent of glaciation.

NBS target lake and stream popluations represent a sensitive subset of the lakes and streams within the three regions:

- ADIRONDACK LAKES: About 700 lakes, approximately 45 percent of the lakes in the Adirondack region meeting ELS sampling requirements
- MID-APPALACHIAN STREAMS: About 4,300 stream reaches, approximately 17 percent of the region's total stream reaches
- SOUTHERN BLUE RIDGE PROVINCE STREAMS: About 1,300 stream reaches, approximately 65 percent of the region's stream reaches meeting the sampling requirements described above

The target populations used in the NBS therefore, represent the best available data for case studies of sensitive regions in the United States.

historically cleared for agriculture predominate along the more-weatherable, more-fertile valleys.

Southern Blue Ridge Province

This region includes potentially sensitive stream reaches in the extreme western portions of North Carolina, South Carolina, eastern Tennessee, and northern Georgia (Exhibit 5).[34] The SBRP includes

[34] This summary for the Sourthern Blue Ridge Province is primarily drawn from Elwood, J.W., M.J. Sale, P.R. Kaufman, and G.F. Cada. 1991. The Southern Blue (continued)

a steep mountainous region characterized by high rainfall, highly weathered base-poor soils, and relatively unreactive bedrock. Target surface waters of this region contain some of the lowest concentrations of dissolved solids of any region sampled in the United States, and among the highest deposition rates for H^+, SO_4^{2-}, and NO_3^-. This area includes the Great Smoky Mountains National Park. Although no acidic streams (ANC≤0 μ eq/l) were found during the NSS, statistical analysis of the results from this study indicated that a small number representing less than 1 percent of the streams in the region may be acidic or be affected acidic episodes. Also, a separate non-random survey during 1982–1984 found 3 percent of the small streams in the region to be acidic; no larger acidic streams were reported in this study.[35]

Watershed retention of SO_4^{2-} and NO_3^- is the major process generating ANC in drainage lakes within this region, exceeding base cation mobilization in importance. Sulfur and nitrogen retention capacities are generally similar and provide relatively consistent sources of ANC across the region. The primary cause of ANC differences in these streams appears to be different rates of acidic cation mobilization from the region's watersheds. Dissolved organic carbon concentrations are typically low and do not appear to provide significant contributions to stream acidity.

Concentrations of SO_4^{2-} have increased at an annual rate of approximately 1 μeq/l during the 10 years prior to 1993 in selected streams draining both high- and low-elevation watersheds. Over the same period both ANC and base cation concentrations declined, indicating that base cation mobilization is not keeping pace with acidic deposition. Despite this, no adverse biological effects from acidic deposition on streams and lakes have been conclusively demonstrated for the SBRP.

The DDRP projected changes in target surface water chemistry for one or two sulfur deposition scenarios, while holding nitrogen deposition and retention constant, using up to three watershed models. Model projections were compared among the three DDRP regions.

Results for the Northeast indicated that these target lakes would likely respond relatively rapidly to changes in sulfur deposition, because Northeast watersheds appear, on average, to be near sulfur steady state. That is, annual loads of atmospheric sulfur deposited into most watersheds approximately equal loads discharged with waters draining from the watersheds. Remaining sulfur retention capacities of Northeast soils appear to be generally limited. In contrast, DDRP projected that at either current or increased sulfur deposition loadings, it might take 150-200 years, on average, before SBRP watersheds attain sulfur steady state. That is, sulfur retention potentials appear much greater in the SBRP than in the Northeast.

Watersheds in the mid-Appalachians have sulfur retention characteristics similar to some Northeast and some SBRP watersheds. As such, they appear to represent a transition region where some systems will likely respond relatively rapidly to changes in sulfur deposition rates, whereas other systems may respond more slowly. Projections of times necessary to reach sulfur steady state averaged about 50 years for the mid-Appalachians watersheds. Further, in contrast to the lack of currently acidic SBRP streams, about 4 percent of the DDRP target population stream reaches in the mid-Appalachians are now chronically acidic. Acidic sulfur deposition appears to be the most likely cause of surface water acidity in mid-Appalachian streams; sulfate from atmospheric sources dominates the strong acid anion component in these streams.

Results of the DDRP model projections for the target populations in each of the three regions studied and for the sulfur deposition scenarios modeled for purposes of the NAPAP 1990 Integrated Assessment Report can be summarized as follows. For lakes in the Northeast, the 1990 CAAA was projected to reduce the loss of habitat for sensitive fish species between 1990 and 2030 by 16 percent to 18 percent from that which was projected to occur without the CAAA. The results also projected that a decrease in sulfur deposition of 30 percent from 1985 levels would lead to increases in lake ANC and decreases in the numbers of chronically and episodically acidic lakes in the Northeast through the last year of the DDRP model projection, 2030.

Ridge Province. Pages 319-364 in D. F. Charles (editor). *Acidic Deposition and Aquatic Ecosystems Regional Case Studies*. Springer-Verlag, New York, NY.

[35] Winger, P.V., P.J. Lasier, M. Hudy, D.L. Fowler, and M.J. Van Den Avyle, 1987. Sensitivity of high-elevation streams in the Southern Blue Ridge Province to acidic deposition. *Water Resources Bulletin* 23:379-386.

The DDRP model projections for the SBRP indicated that continued sulfur deposition at 1985 levels for 50 years would increase stream sulfur concentrations and decrease stream ANC, with the result that a small percentage of the DDRP target population stream reaches might become chronically acidic in 50 years. There might also be a slight increase in the number of stream reaches susceptible to acidic episodes.

In the mid-Appalachians at the 1985 rate of sulfur deposition, the DDRP model projected that in 50 years the proportion of target acidic (ANC≤0 μeq/l) stream reaches would increase between 3 percent and 11 percent. This scenario also is projected to double, from 25 percent to 54 percent, the target population of stream reaches that have an ANC less than 50 μeq/l. This would also double the number of stream reaches potentially susceptible to acidic episodes. Models of a deposition scenario involving a 50 percent decrease from 1985 sulfur deposition rates projected that increases in stream ANC would occur in 50 years across the DDRP target population (although statistically significant changes in the number of acidic reaches or reaches with ANC less than 50 μeq/l were not expected).

2.5.3 Nitrogen Bounding Study

Evidence and concern regarding long-term surface water acidification associated with nitrogen deposition and NO_3^- leaching from watersheds is increasing as some watersheds appear to be approaching nitrogen saturation (see Section 2.2.1). The relative importance of nitrogen deposition is also becoming more apparent as adverse effects from sulfur deposition are apparently easing in response to the 1990 CAAA and earlier SO_2 emissions reductions.

Exhibit 7 presents NBS model projections of percentages of acidic and sensitive surface waters (ANC≤0 μeq/l and ANC≤50 μeq/l) in three regions of the eastern United States in the year 2040 under three scenarios: (1) without the 1990 CAAA (sulfur deposition held constant at 1993 levels and a 1 percent annual increase in nitrogen deposition after the year 2000); (2) without the 1990 CAAA sulfur reductions (sulfur deposition held constant at 1993 levels) but with the nitrogen controls (nitrogen deposition held constant at 1985 levels); and (3) with implementation of the CAAA sulfur and nitrogen controls (nitrogen deposition held constant at 1985 levels). Results of these three scenarios illustrate the proportion of surface waters that would likely have been acidic or sensitive to becoming acidic had there been no CAAA. These modeling projections are subject to the uncertainties described previously. As such, they indicate approximate proportions of the surface water target populations projected to have ANC≤0 or 50 μ eq/l for the indicated deposition scenarios. The scenario depicting no sulfur reductions and a 1 percent annual increase in nitrogen deposition is intended to be representative of a situation without CAAA reductions (no sulfur reductions and a continuing increase in nitrogen deposition). The exhibit shows that the reduction in sulfur deposition levels resulting from the 1990 CAAA are projected to provide clear benefits in improving ANC and reducing acid stress in the lakes and streams of the three regions that hold a major proportion of sensitive aquatic resources in the eastern United States.

EPA designed the NBS to begin providing a more complete understanding of potential effects attributable to nitrogen deposition during surface water acidification.[36] This study examined the combined effects on surface water chemistry due to potential changes in the deposition rates of total sulfur and total nitrogen, and due to possible alternative rates of nitrogen saturation within watersheds. Projected surface water chemistry for two target years (2015 and 2040) were assessed, with the assumption that emissions reductions mandated by the 1990 CAAA (the permanent 10 million tons of SO_2 and the temporary 2 million tons of NO_x) were fully implemented.

The study evaluated target populations of surface waters in three regions: lakes in the Adirondack Region and stream reaches in the mid-Appalachians and the Southern Blue Ridge. Target populations of waters modeled are described in Exhibit 6. The NBS model projections were completed using a modification of the MAGIC model (see Exhibit 4). The primary input data came from the NSWS, DDRP studies, and updated deposition information from the EPA atmospheric modeling studies discussed in Chapter 3. The NBS results represent responses for proportions of NBS modeled systems; they do not represent responses for either all surface waters or for all NSWS sampled surface waters in the modeled regions.

[36] Van Sickle, J., and M.R. Church. 1995. Methods for Estimating the Relative Effects of Sulfur and Nitrogen Deposition on Surface Water Chemistry. U.S. Environmental Research Laboratory, Corvallis, OR.

EXHIBIT 7. IMPACT OF CAAA ON SENSITIVE SURFACE WATERS: NBS MODEL PROJECTIONS FOR YEAR 2040

PROPORTIONS OF TARGET POPULATION SURFACE WATERS IN TWO ANC CATEGORIES FOR THREE DEPOSITION SCENARIOS (SEE TEXT FOR ADDITIONAL DETAILS)

Region	Criterion	Deposition Scenario	Observed Proportion[a]	Proportions (Percentages) at Modeled Times to Watershed Nitrogen Saturation			
				50 years	100 years	250 years	Never
ADIR	ANC≤0 μeq/l	w/o CAAA: 1% N increase[b]	19	52	39	23	24
		w/o CAAA: Constant N[c]		50	36	23	25
		CAAA[d]		43	26	15	11
	ANC≤50 μeq/l	w/o CAAA: 1% N increase[b]	55	77	59	55	55
		w/o CAAA: Constant N[c]		74	58	55	55
		CAAA[d]		67	57	54	54
M-APP	ANC≤0 μeq/l	w/o CAAA: 1% N increase[b]	4	42	28	23	21
		w/o CAAA: Constant N[c]		33	23	21	8
		CAAA[d]		9	5	4	0
	ANC≤50 μeq/l	w/o CAAA: 1% N increase[b]	27	76	66	65	49
		w/o CAAA: Constant N[c]		67	54	48	38
		CAAA[d]		41	37	28	23
SBRP	ANC≤0 μeq/l	w/o CAAA: 1% N increase[b]	0	14	7	2	0
		w/o CAAA: Constant N[c]		13	2	1	0
		CAAA[d]		4	0	0	0
	ANC≤50 μeq/l	w/o CAAA: 1% N increase[b]	6	31	22	17	15
		w/o CAAA: Constant N[c]		20	17	15	15
		CAAA[d]		16	16	14	11

[a] Observed in 1984 in Adirondacks and 1985 in Mid-Appalachians and Southern Blue Ridge.

[b] Sulfur deposition held constant at 1993 levels; nitrogen deposition increases 1% per year after 2000.

[c] Sulfur deposition held constant at 1993 levels; nitrogen deposition held constant at 1985 levels.

[d] Reflects only decreases in sulfur deposition from implementation of Title IV; nitrogen deposition held constant at 1985 levels.

The NBS study is the most recent major study having important implications for considering the feasibility of aquatics-based acid deposition standards in the United States. Therefore, it is valuable to understand clearly the nature of the results produced by this study. Exhibits 8–10 present 3 of over 60 similar sets of four plots presenting NBS model results. These sets of plots show modeled responses for percentages of the target population of Adirondack Region lakes projected to meet the criterion of ANC of 0 μeq/l or less in the year 2040 and the percentages of target populations of mid-Appalachians and SBRP stream reaches projected to meet the criterion of ANC of 50 μeq/l or less in year 2040. Exhibit 11 provides guidance for interpretation of the NBS plots presented in Exhibits 8–10 and in Appendix B.

Times to watershed nitrogen saturation in these systems remain a major uncertainty. Some modeling and empirical analyses (for example, at Hubbard Brook in New Hampshire and the Harvard Forest in Massachusetts) indicate rather long times to nitrogen saturation, while other results from the experimentally manipulated watersheds of Bear Brook in Maine and Fernow in West Virginia indicate shorter response times to increased nitrogen additions. Also, nitrate concentrations have noticeably increased recently in some surface waters draining the Catskills, Adirondacks, and the highest elevation spruce stands in the Great Smoky Mountains, suggesting that *some* watersheds in these regions are moving toward or have reached nitrogen saturation. Consequently, evaluating current trends for nitrogen saturation on a regional basis remains very difficult. To accommodate this uncertainty, the NBS model projections assumed constant rates of nitrogen assimilation (i.e., no change from present) and included scenarios of time to watershed nitrogen saturation of 50, 100, and 250 years. Additional considerations regarding

EXHIBIT 8. NBS MODEL PROJECTIONS FOR YEAR 2040 PERCENTAGE OF TARGET POPULATION ADIRONDACK LAKES WITH ANC≤0 µEQ/L

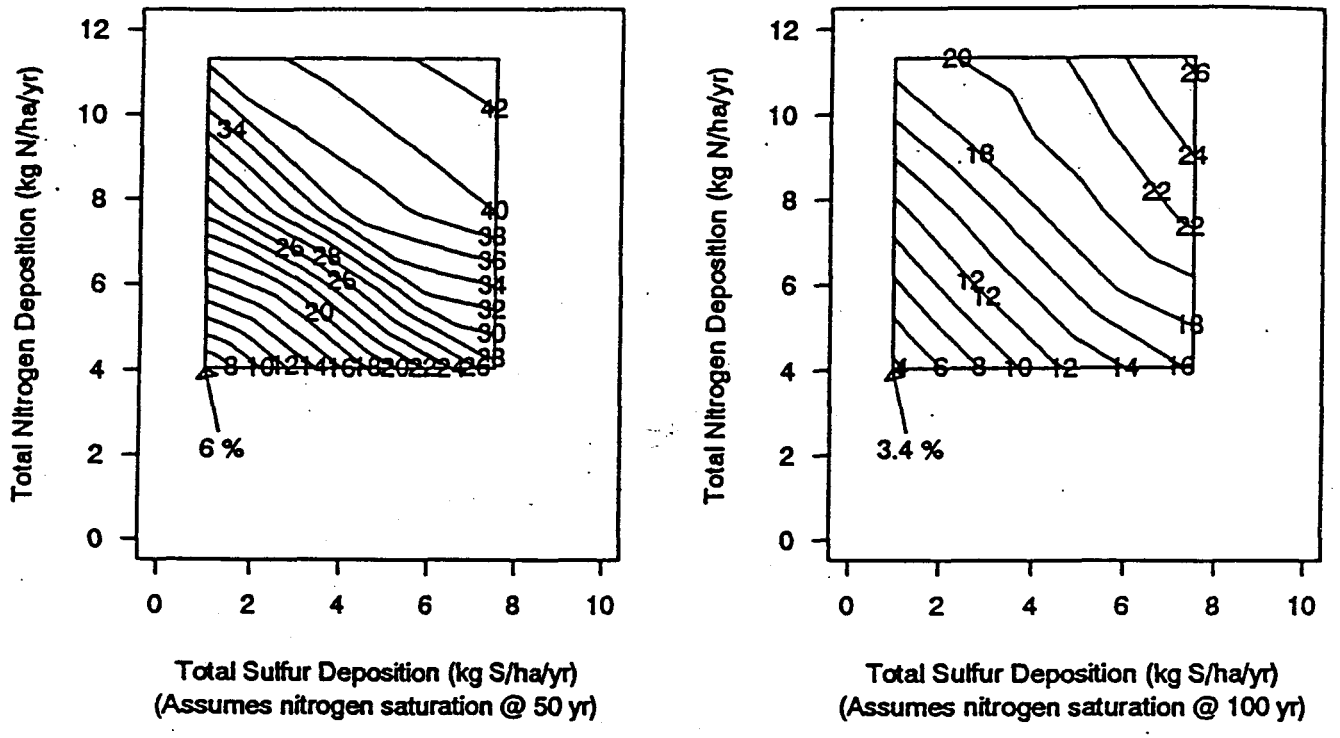
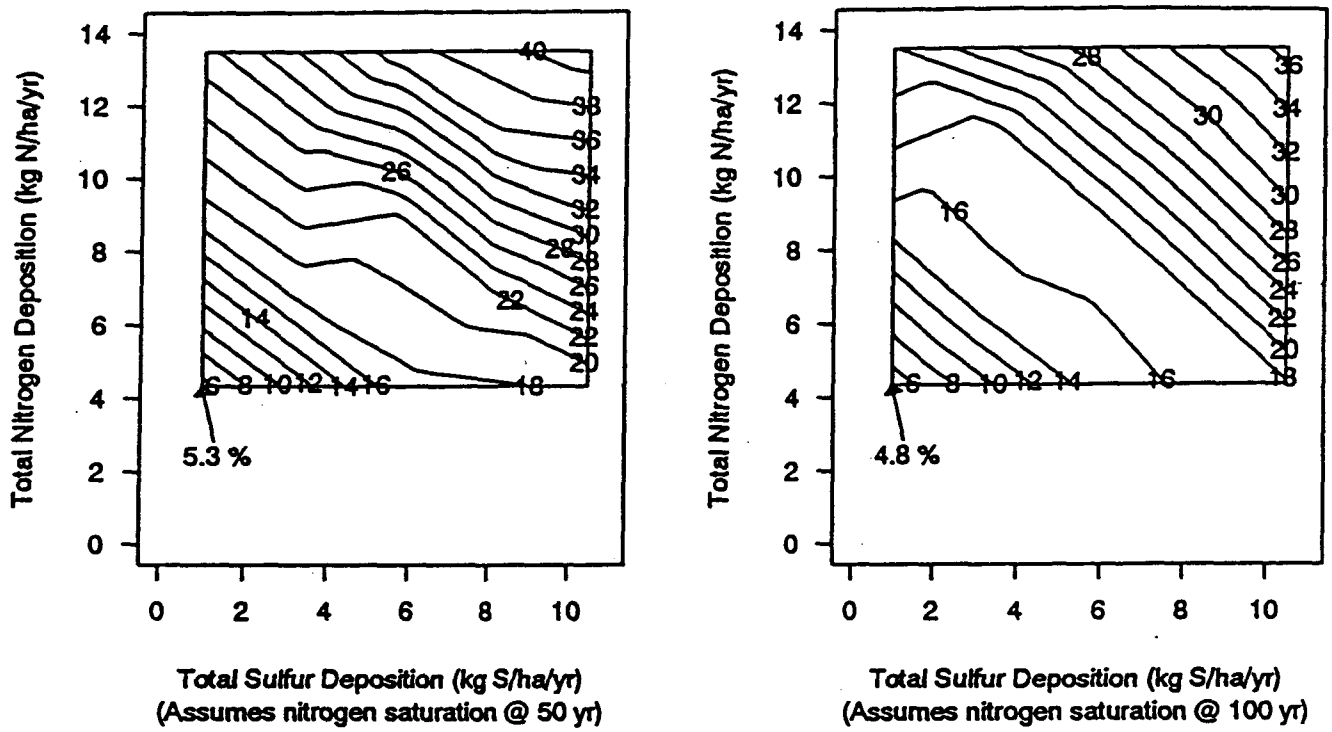


EXHIBIT 9. NBS MODEL PROJECTIONS FOR YEAR 2040 PERCENTAGE OF TARGET POPULATION MID-APPALACHIAN STREAMS WITH ANC≤ 50 μEQ/L



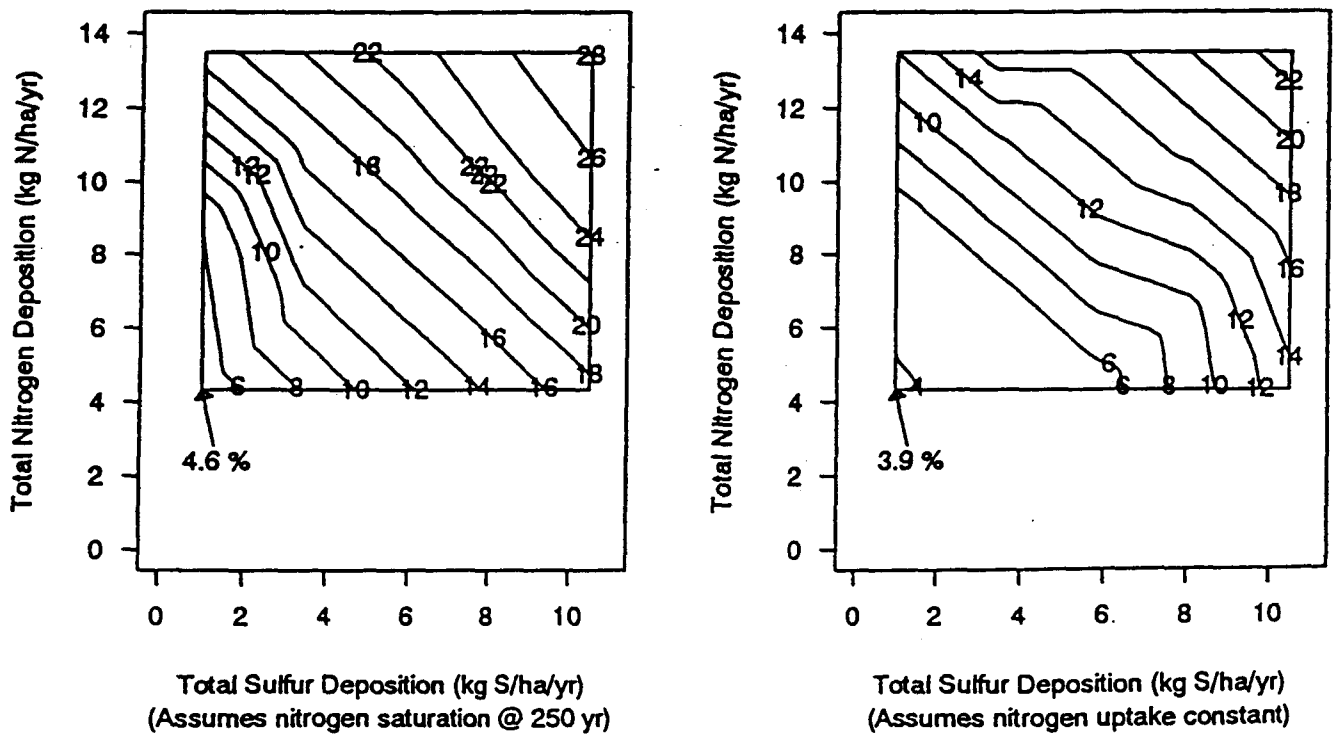
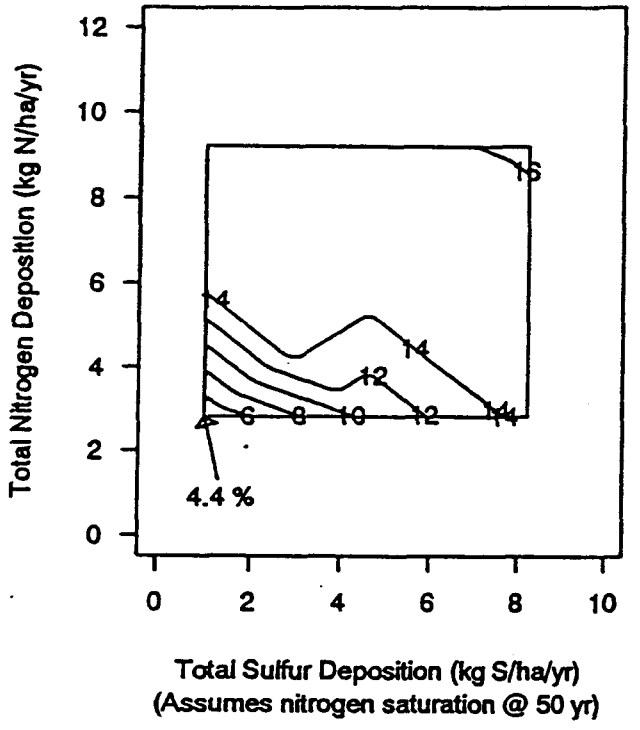
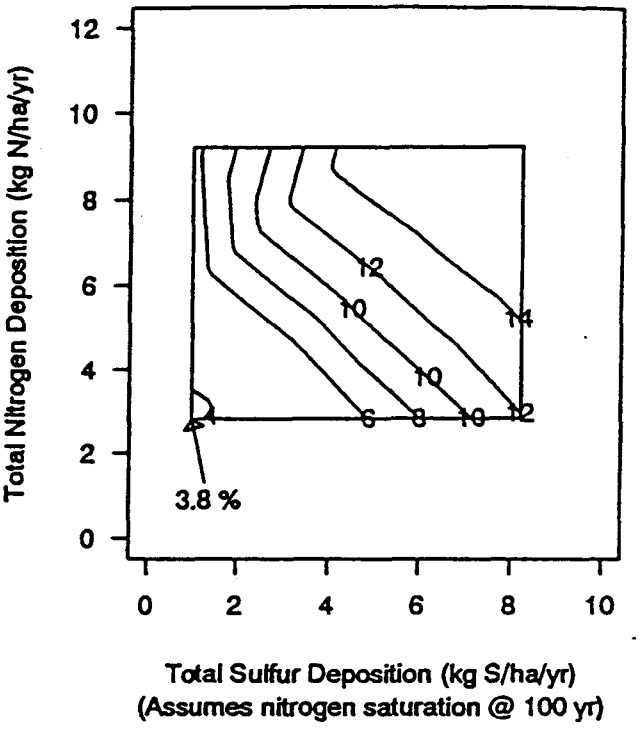
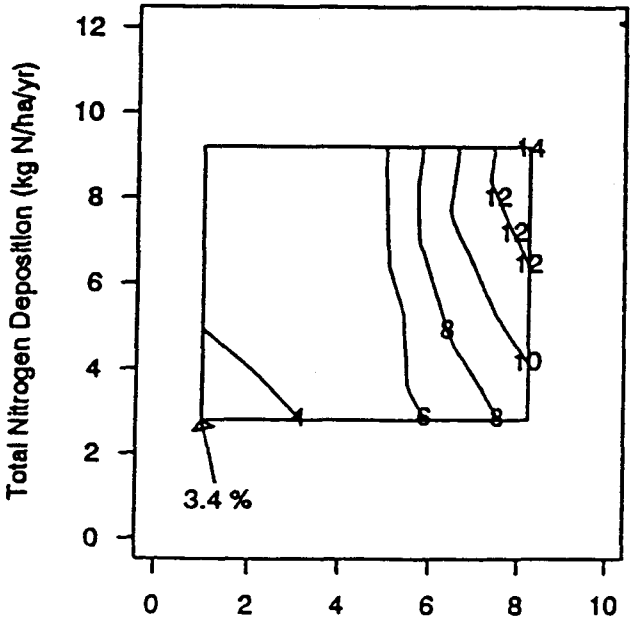


EXHIBIT 10. NBS MODEL PROJECTIONS FOR YEAR 2040 PERCENTAGE OF TARGET POPULATION SOUTHERN BLUE RIDGE STREAMS WITH ANC≤50 µEQ/L







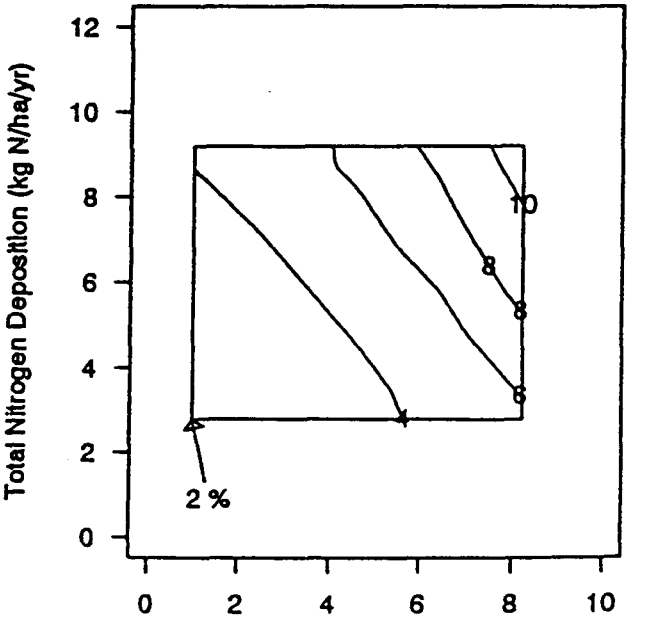


EXHIBIT 11. INTERPRETING NBS PLOTS

To illustrate interpretation of the NBS plots, the four individual plots in Exhibit 8 show projected percentages of NBS target population lakes in the Adirondack Mountains with ANC of 0 μeq/l or less, where watershed nitrogen saturation is assumed to occur at 50, 100, and 250 years, as well as where watershed assimilation rates for nitrogen remain constant at recently estimated rates (i.e., watershed nitrogen saturation will never occur). Response contours for each plot show how percentages of target waters are projected to vary with changes in total sulfur and nitrogen deposition throughout the modeled ranges of deposition. These ranges begin at projected background deposition rates for sulfur and nitrogen (1 kg S/ha/yr and 4 kg N/ha/yr) and extend to their maximum modeled concentrations for 2040 (7.5 kg S/ha/yr and 11.3 kg N/ha/yr), i.e., the rates projected to accompany implementing the 1990 CAAA (see Chapter 3). Thus, for the upper right plot of Exhibit 8, which shows projections based on an assumed 100 years to nitrogen saturation, the model projects that approximately 26 percent of the target Adirondack lakes may be acidic (ANC 0 μeq/l) at year 2040 for modeled sulfur and nitrogen deposition rates projected to accompany implementation of the 1990 CAAA. With only background deposition of sulfur and nitrogen, 3.4 percent of these target lakes are projected to be acidic at 2040.

Several general observations apply to these plots:

- The slopes of contour lines in each plot reflect the relative importance of sulfur and nitrogen in causing the projected response relationships. Nearly vertically plotted response contours indicate that the projected ANC response is attributable primarily to sulfur deposition. Nearly horizontal plotted response contours indicate the plotted ANC response is attributable primarily to nitrogen deposition. A forty-five degree diagonal contour indicates equal contributions by both sulfur and nitrogen depositions.
- Changes in the spacing between individual response contours within each plot appears to be attributable to patterns in sample weighting during model projections, rather than due to some intrinsic character of the deposition-response relationships.
- The density of response contours across the modeled deposition ranges for each plot directly relates to the potential average responsiveness by target waterbodies to potential changes in sulfur and nitrogen deposition rates on the specified water quality classification variable modeled (e.g., ANC≤0 μeq/l). Therefore, plots with a high density of contour lines depict a high level of responsiveness to changes in deposition.

possible regional difference in times to nitrogen saturation are presented in Exhibit 12.

For these plots, deposition rates of sulfur and nitrogen were assumed to be those projected to accompany implementation of the 1990 CAAA to the year 2010. At that time, different sulfur and nitrogen deposition scenarios were defined and modeled. Some modeled scenarios maintained the 2010 deposition rates, while some alternative modeled scenarios declined to background deposition rates. Rates for still other scenarios reduced to levels between these extremes. (*Background deposition* rates include only natural, agricultural fertilizer, and domestic livestock sources.) Each modeled deposition rate was then assumed to remain constant at the modeled 2020 rate until the year 2040, the end of the model projection period.

Sets of plots similar to those shown in Exhibits 8–10 have been produced through this study projecting year 2040 proportions of NBS target surface waters within each of the three modeled regions meeting five evaluation criteria: ANC≤ 0 μeq/l, ANC≤50 μeq/l, pH≤5.0, pH≤5.5, and pH≤ 6.0. Similar plots for all four water chemistry criteria were also produced for the year 2015. All other NBS plots showing results of both ANC and pH projections are presented in Appendix B.

Because of uncertainties associated with the complex chemical relationships modeled in MAGIC's derivations for pH, ANC projections are considered to be more reliable than those for pH. As previously described, ANC is an important indicator of sensitivity to acidification (see Section 2.3.1). Furthermore, projected water quality changes are

EXHIBIT 12. TIME TO WATERSHED NITROGEN SATURATION

Present scientific knowledge does not allow quantifying the time to nitrogen saturation for any of the three study regions considered in the NBS, and no scientific consensus exists regarding actual times to nitrogen saturation for watersheds within these three regions or any others regions. Indeed, NBS investigators and most of this project's technical reviewers deem it scientifically premature to define specific times to saturation for any region. Yet, it is reasonable to suggest that times to saturation do vary among regions. This variation is due primarily to differences in temperature, moisture, soil fertility, primary production rates, decomposition rates, forest age, and the accumulation of plant biomass, along with different histories of nitrogen deposition among the regions. Further, given historic and current nitrogen deposition rates in these three regions, it is reasonable to assume that forested watersheds would eventually reach nitrogen saturation (barring major disturbances such as logging, major fires, blow downs, and insect infestations).

As a speculative example, watersheds in the Adirondacks have cooler annual temperatures, shorter growing seasons, lower inherent productivity potentials, restrictive logging practices and fire control policies, very mature old-growth forest stands, and long histories of elevated deposition rates of sulfur and nitrogen. Consequently, watersheds in these areas may include those having the shortest remaining times to nitrogen saturation. It has been suggested that saturation times in this region may average less than 100 years; some even suggest the range of 25 to 75 years. In comparison, moving to a more southerly region, watersheds in the Mid-Appalachians have generally warmer annual temperatures, longer growing seasons, less restrictive forestry practices, and greater inherent productivity potentials, while also having high nitrogen deposition rates. Watersheds in this region may have somewhat longer remaining times to nitrogen saturation. Finally, watersheds in the Southern Blue Ridge Province have even warmer annual temperatures, longer average growing seasons, relatively the greatest productivity potentials, the fastest decomposition rates, historically lower nitrogen deposition rates, much smaller pools of soil nitrogen, and generally very low stream nitrogen concentrations. Here, the remaining time to watershed nitrogen may be greater still. Some areas in this region such as those found in the Great Smoky Mountains National Park also include mature old-growth forests and other forests which have sustained previous damage (i.e., insect damage). Time to nitrogen saturation would likely be shorter in these areas. Estimated times to watershed nitrogen saturation for each region are uncertain, but the relative ranking of these times is likely appropriate across the three broad regions modeled.

likely to be highly transient in nature for the year 2015, largely because potential benefits from implementation of 1990 CAAA requirements will still be accruing at that time. Therefore, this section focuses primarily on projected ANC changes in the year 2040. For those also interested in projected changes in pH, the ANC changes discussed can be related to corresponding pH changes using the empirical relationships between these variables presented in Exhibit 1: on average, across the three NBS regions, ANC≤0 μeq/l and ANC ≤50 μeq/l approximate pH≤5.3 and pH≤6.5, respectively. NBS plot projection for pH changes are presented in Appendix B.

Summary of NBS Results

Exhibit 13 summarizes the observed and modeled percentages of surface waters in each NBS region target population for both ANC criteria. The observed values were those measured during the 1984 NSWS studies in the Adirondacks and the

1985 studies in the other two regions. For example, 19 percent of the target lakes in the Adirondacks used during the NBS were observed to be acidic (ANC≤0 μeq/l) during the 1984 NSWS. Note, however, that the target population of the NBS modeling included generally more sensitive subsets of target population surface waters than were included in the NSWS (see Exhibit 6).

The modeled projections summarized in Exhibit 13 indicate proportions of surface waters in the two ANC categories by the year 2040 under the assumed times of 50 to 250 years and never for watershed nitrogen saturation for each region. This range brackets the modeled times for watershed nitrogen saturation occurring across the three NBS regions for proportions of waters within each ANC category. The percentages presented encompass the range of NBS results for modeled

EXHIBIT 13. SUMMARY OF NBS RESULTS: RANGE OF MINIMUM (BACKGROUND DEPOSITION) TO MAXIMUM (IMPLEMENTATION OF CAAA) PERCENTAGES OF ACIDIC AND SENSITIVE TARGET WATERS

	Percentage of Target Waters		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
Acidic (ANC≤0 μeq/l)			
Observed[a]	19	4	0
Projected 2040, nitrogen saturation in 50 yr	6–43	0–9	0–4
Projected 2040, nitrogen saturation in 100 yr	3–26	0–5	0–0
Projected 2040, nitrogen saturation in 250 yr	0–15	0–4	0–0
Projected 2040, nitrogen saturation never	0–11	0–0	0–0
Sensitive (ANC≤50 μeq/l)			
Observed[a]	55	27	6
Projected 2040, nitrogen saturation in 50 yr	53–67	5–41	4–16
Projected 2040, nitrogen saturation in 100 yr	51–57	5–37	4–16
Projected 2040, nitrogen saturation in 250 yr	44–54	5–28	3–14
Projected 2040, nitrogen saturation never	44–54	4–23	2–11

[a] Observed 1984 for Adirondack lakes and 1985 for mid-Appalachian and Southern Blue Ridge streams.

minimum (background) and modeled maximum (projected 1990 CAAA deposition) rates for both total sulfur and nitrogen. For example, with an assumed time to watershed nitrogen saturation of 100 years, the upper right plot of Exhibit 8 shows that background total sulfur and nitrogen deposition in the Adirondacks is projected to result in 3.4 percent of the target lakes having ANC of 0 μeq/l or less in the year 2040. Similarly, the maximum deposition for both anions likely under implementation of the 1990 CAAA are projected to result in about 26 percent of the target lakes in this water quality class. Also, under this same range of deposition scenarios, when the time to watershed nitrogen saturation is assumed to equal 250 years, the lower left plot in Exhibit 8 shows that the model projects that between 0 percent and 15 percent of these same target Adirondack lakes will have ANCs of 0 μeq/l or less. Exhibit 13 shows these two ranges and summarizes all other similar NBS projections for ANC by the year 2040 for all three modeled regions.

The numerical ranges in the model projections presented in Exhibit 13 provide an indication of the extent of uncertainty associated with each set of model projections for each region. For example, with the modeled rates of sulfur and nitrogen deposition expected to accompany implementation of the 1990 CAAA, the percentage of target lakes in the Adirondacks with ANCs of 0 μeq/l or less would likely range from about 15 percent to 43 percent, depending on whether the true time to watershed nitrogen saturation is nearer 250 or 50 years, respectively. As discussed previously, a variety of sources of variability and uncertainty affect the overall uncertainty of these model projections. If these sources were included in an overall evaluation of uncertainty, the associated uncertainty could be greater, with projections of future responses by target waterbody populations potentially falling beyond either end of all modeled ranges presented in Exhibit 13. Therefore, while the NBS projections of change represent the best currently available techniques for projecting environmental changes associated with acidic deposition, the projections are best used as indicators of general direction and magnitude of possible water quality changes associated with changes in total sulfur and total nitrogen deposition rates (See Exhibit 6).

As noted in Exhibit 11, the density of contours across the modeled deposition ranges in NBS plots for ANC, including those in Exhibits 8–10, appears to relate to the potential average responsiveness of target waterbodies to potential changes in deposition rates. (Vertical and horizontal contours indicate a strong role of sulfur or nitrogen, respectively.) Based on this relationship, all regional plots for alternative projected times to watershed nitrogen saturation were categorized into one of three generalized levels of projected response sensitivities. These categories provide a basis for evaluating the relative confidence that reducing sulfur or nitrogen depositions below levels projected to accompany the 1990 CAAA would produce detectable improvements in ANC within the

NBS target surface waters. Exhibit 14 presents the results of the surface water responsiveness categorization for the three modeled regions. The following summary of regional relationships to acidic deposition rates is drawn from Exhibits 13 and 14 and from the individual plots for all three NBS study regions.

Regional Summaries[37]

Adirondack Region

ROLES OF SULFUR, NITROGEN AND NATURAL ACIDITY: For the NBS target population of Adirondack lakes, after implementation of the 1990 CAAA, sulfur deposition appears to continue to be the primary cause of the present chronically acidic surface water chemistry when longer modeled times to nitrogen saturation (≥250 years) are assumed. Nitrogen and sulfur deposition are projected to share relatively equal future roles in affecting modeled ANC when watershed nitrogen saturations are as-

EXHIBIT 14. SURFACE WATER RESPONSIVENESS TO REDUCTIONS IN DEPOSITION BEYOND THE CAAA: DETECTIBLE IMPROVEMENTS IN LONG-TERM ANC BY 2040[a,b]

Region	Deposition Parameter Reduced	Criterion (ANC)	Estimated Time to Watershed Nitrogen Saturation			
			50 Years	100 Years	250 Years	Never
ADIR	Sulfur	≤0 μeq/l	▲	▲	▲	▲
	Sulfur	≤50 μeq/l	●	O	●	●
	Nitrogen	≤0 μeq/l	▲	▲	O	O
	Nitrogen	≤50 μeq/l	▲	O	O	O
M-APP	Sulfur	≤0 μeq/l	O	O	O	O
	Sulfur	≤50 μeq/l	▲	▲	▲	▲
	Nitrogen	≤0 μeq/l	●	O	O	O
	Nitrogen	≤50 μeq/l	▲	▲	▲	▲
SBRP	Sulfur	≤0 μeq/l	O	O	O	O
	Sulfur	≤50 μeq/l	O	●	▲	●
	Nitrogen	≤0 μeq/l	O	O	O	O
	Nitrogen	≤50 μeq/l	●	●	O	O

[a] Key to symbols:

- O Additional decrease in acidic deposition of **any magnitude** below 1990 CAAA requirements is **unlikely** to produce improved conditions.
- ● Additional decrease in acidic deposition of **at least 50%** below 1990 CAAA requirements **may** produce improved conditions. **Lesser reduction** in deposition is **unlikely** to produce improved conditions.
- ▲ Additional decrease in acidic deposition of **at least 50%** below 1990 CAAA requirements is **likely** to produce improved conditions. **Lesser reduction** in deposition **may** produce improved conditions.

[b] **Improved conditions** is defined as decreases by greater than 5% of the **target population** (e.g., from 30% to 24%) meeting the specified criterion (e.g., ANC≤50 μeq/l), assuming the specified time as the region average for watershed N saturation. Reduced deposition may lead to environmental improvement which does not meet the definition of "improved conditions" described above.

Because the strongest scientific data collected on acidity in the eastern lakes and streams come from the 1984 NSWS, the water quality conditions found in that survey serve as a model for protective goals used in this report.

[37] Most of this discussion was developed from evaluations of results from the National Surface Water Survey and model projections from the Nitrogen Bounding Study.

sumed to occur within 100 years. And, when 50 years is assumed as the time to nitrogen saturation, the future importance of nitrogen deposition as a direct cause of surface water acidification is projected to be greater.

Proportions of ANC≤50 μeq/l lakes in this region are projected as likely to show very small changes due to deposition reductions by the year 2040. This relatively small potential for change indicates that this region has a high proportion of lakes which naturally have ANCs of 50 μeq/l or less without the influence of acidic deposition. These lakes will continue to have low ANC levels regardless of acidic deposition rates. This condition is not detrimental in itself, but makes these waters highly sensitive to adverse effects from episodic acidic events.

CHRONIC ACIDIFICATION: Under an assumed time to watershed nitrogen saturation of 50 years and under the deposition reductions projected from 1990 CAAA implementation, the proportion of chronically acidic (ANC≤0 μeq/l) Adirondack target lakes is projected to increase by about 50 percent in 2015 and may double by 2040, relative to 1984 proportions. Assuming 100 years to nitrogen saturation, NBS modeling projects that with implementation of the 1990 CAAA, proportions of ANC ≤0 μeq/l lakes in the NBS target population may increase from 19 percent in 1984 to 26 percent in 2040. These increased proportions appear due largely to the increased effects of nitrogen deposition. If, however, the time to nitrogen saturation equals or exceeds 250 years, the model projects a slight reduction in the proportion of acidic lakes in 2040 with the implementation of the 1990 CAAA (i.e., from 19 percent to 15 percent or less). The uncertainty regarding time to watershed nitrogen saturation remains an important consideration.

EPISODIC ACIDIFICATION:[38] Two parallel but independent estimates place the number of Adirondack lakes within the NBS target population that may become acidic (i.e., ANC≤0 μeq/l) during snowmelt or heavy storm flow events at least once per year at about 3.5 times the number of chronically acidic lakes. The 1984 proportion of NBS target population lakes estimated to be at risk of episodic acidification at least once per year is 73 percent, compared to 19 percent estimated to be chronically acidic. Because episodes are driven principally by deposition acidity, reductions in acidic deposition rates for either sulfur, nitrogen, or both can be expected to significantly reduce the occurrence of acidic episodes in the target population of Adirondack lakes. This would be expected to occur at a more rapid rate than the reduction in proportions of chronically acidic lakes because deposition reductions are likely to have the greatest immediate influence in reducing the mass of acids and acid anions deposited by major storms.

RESPONSIVENESS TO DEPOSITION REDUCTIONS: Modeling results for the NBS target population of Adirondack lakes indicate a reasonable expectation that additional reductions in sulfur deposition rates, beyond those projected to accompany the 1990 CAAA, would likely produce detectable long-term improvements in ANC, regardless of the time to nitrogen saturation for the NBS target watersheds. It is also reasonable to expect that reduced nitrogen deposition would produce detectable ANC changes in these lakes, but primarily if times to nitrogen saturation for these watersheds average 100 years or less.

While considerable uncertainty regarding time to watershed nitrogen saturation exists, if the average time for Adirondack watersheds to reach nitrogen saturation is close to 100 years or less, the model predicts that maintaining the proportion of chronically acidic (ANC≤0 μeq/l) target population Adirondack lakes near their 1984 proportions in 2040 may require reducing anthropogenic sulfur and nitrogen deposition by 40–50 percent or more below the reductions projected to accompany the 1990 CAAA. The model projects that reductions in sulfur and nitrogen deposition of about 4.5 kg-S/ha/yr and 7.5 kg-N/ha/yr, are projected as necessary to maintain proportions of sensitive lakes (ANC≤50 μeq/l) near their 1984 levels (i.e, 55 percent) *if* the time to watershed nitrogen saturation approaches 50 years or less. If the time to saturation actually is 100 years or longer, the model projects that deposition reductions accompanying the 1990 CAAA will allow proportions of Adirondack lakes with ANC≤50 μeq/l to maintain their approximate 1984 levels to the end of the projection interval at the year 2040.

Mid-Appalachian Region

ROLES OF SULFUR AND NITROGEN: For the NBS target population of mid-Appalachians stream reaches assessed, model projections indicate that sulfur and nitrogen deposition appear about equally important in surface water acidification processes for this region (Exhibit 9).

[38] Also see Section 2.2.2 on episodic acidification.

CHRONIC ACIDIFICATION: As progressively shorter times to watershed nitrogen saturation are assumed, adverse effects associated with nitrogen deposition are projected to increase, essentially offsetting reduced proportions resulting from implementation of the 1990 CAAA sulfur reductions in mid-Appalachians target streams. Under assumptions of 250 years or less as the time to watershed nitrogen saturation, no net change in the proportion of acidic (ANC≤0 μeq/l) streams in the NBS target population is projected to accompany implementation of the 1990 CAAA.

EPISODIC ACIDIFICATION: The estimated number of mid-Appalachians stream reaches in the NBS target population that are episodically acidic (ANC≤ 0 μeq/l) at least once per year under 1985 deposition levels is approximately six times the number estimated to be chronically acidic (i.e., approximately 23 percent of the target stream reaches likely experience acidic episodes). Reducing deposition of sulfur, nitrogen, or both would be expected to reduce the number of episodically acidic stream reaches in the mid-Appalachians target population faster than the rate of reduction for chronically acidic reaches, for reasons similar to those concluded for Adirondack lakes, above.

RESPONSIVENESS TO DEPOSITION REDUCTIONS: Potential benefits from additional deposition reduction beyond the 1990 CAAA is projected to have benefits for the target population of mid-Appalachians stream reaches having ANCs of 50 μeq/l or less, regardless of the time to nitrogen saturation. The nature of these benefits should be viewed not so much as potentially reducing chronically acidic conditions in these target streams (although this is likely), but as potentially reducing the susceptibility of sensitive streams to episodic acute acidification effects (i.e., decreasing the proportion of stream segments with ANC less than 50 μeq/l).

The 1985 Eastern Stream Survey found 27 percent of the NBS target streams in the mid-Appalachians had ANCs of 50 μeq/l or less. NBS projections indicate that if the average time to watershed nitrogen saturation approximates 250 years or greater, implementation of the 1990 CAAA would likely result in target stream reaches maintaining their 1985 proportions of chronically acidic (ANC≤0 μ eq/l) as well as sensitive (ANC≤50 μeq/l) stream reaches in the year 2040. If, instead, average time to watershed nitrogen saturation approximates 100 years or less, the model projects that reducing either sulfur or nitrogen deposition by about 25 percent below projected CAAA reductions, or some lesser combined deposition reduction for both chemicals, could be necessary to maintain proportions of target stream reaches in the year 2040 near their 1985 conditions. That is, the deposition rates may have to be reduced by about 3.5 kg-S/ha/yr or 3 kg-N/ha/yr, or some combination leading to reduced deposition for both acidifying chemicals, if the time to nitrogen saturation approximates 100 years to maintain 1985 proportions.

Southern Blue Ridge Province

ROLES OF SULFUR AND NITROGEN: In the SBRP, like the mid-Appalachians, projected deposition effects after implementation of the 1990 CAAA appear about equally attributable to sulfur and nitrogen deposition. This is probably due to the relatively high remaining potentials for SO_4^{2-} adsorption in soils and NO_3^- retention in watersheds of the SBRP. NBS modeling results project a relatively minor response to deposition changes during the period modeled; more discernible water quality changes related to either sulfur or nitrogen deposition may occur after the year 2040.

CHRONIC ACIDIFICATION: Generally, the NBS target population of stream reaches in this region presently appears to be little affected by chronic acidity. Six percent of the NSWS stream reaches in this region had ANC of 50 μeq/l or less. Under the 1990 CAAA and under all four assumptions of time to watershed nitrogen saturation, the acid chemistry in most target stream reaches are projected to change generally little by 2040 from 1985 conditions. A marked exception to this pattern is that, even with CAAA implementation, the proportion of target stream reaches with ANCs of 50 μeq/l or less are projected to approximately double, reaching 11 percent to 16 percent by 2040, under the modeled times to nitrogen saturation of 250 years or greater. In turn, if nitrogen saturation occurs at about 50 years, about 4 percent of stream reaches might become acidic (ANC≤0 μeq/l) where none previously had been acidic.

EPISODIC ACIDIFICATION: Potential changes in episodic effects within the SBRP were not modeled during the NBS because appropriate model calibration data were lacking, and therefore, no available numeric estimates exist for the percentage of stream reaches in this NBS target population that may become episodically acidic by either 2015 or 2040. Nevertheless, as the number of stream reaches in the SBRP target population with chronic ANC of 50 μeq/l or less increases, the possibility of

episodically acidic conditions increases substantially and can be reasonably expected to occur in these target streams prior to (and at greater percentages than) the occurrence of chronically acidic conditions.

RESPONSIVENESS TO DEPOSITION REDUCTIONS: Model projections indicate that deposition reductions accompanying the CAAA would likely prevent long-term acidification (ANC≤0 μeq/l) of sensitive streams at least until 2040, if the time to nitrogen saturation is 100 years or longer. Modeling projections also indicate that additional reductions in sulfur or nitrogen deposition in the SBRP, beyond those expected to accompany the CAAA, could reduce the proportion of target stream reaches with ANCs of 50 μeq/l or less. If the time to watershed nitrogen saturation in this region is near 250 years or longer, the NBS modeling projects that sulfur deposition would need to be reduced by about an additional 25 percent to maintain the ANCs in the target stream reaches near their 1985 conditions. Whereas, if the time to watershed nitrogen saturation is nearer 100 years or less, a 65 percent total decrease in both sulfur and nitrogen deposition beyond the CAAA is projected as necessary to maintain ANC in these target stream reaches near their 1985 conditions in the year 2040. NBS projections for this potential time to nitrogen saturation (100 years or less) indicate that deposition may have to be reduced below 4 kg-S/ha/yr and below 5 kg-N/ha/yr to maintain proportions of stream reaches in the SBRP target population with ANC≤50 μeq/l at 1985 values.

Implications for an Acid Deposition Standard

The potential sensitivities of target aquatic resources, their potential responses, and time course of responses to changes in acidic deposition rates as well as the relative current and potential roles of sulfur and nitrogen clearly differ among regions. This strongly supports the development of a site-specific deposition standard or target load.

The acidifying effects of nitrogen deposition should be considered when evaluating options and potential needs for acid deposition standards. Specifically, NBS modeling indicates that nitrogen deposition appears to produce important consequences for the future acidification rates of surface waters. Additionally, for many watersheds the effect of nitrogen deposition could be a greater concern than are the effects of sulfur deposition alone.

The wide-ranging projections of possible benefits associated with implementation of the 1990 CAAA for each of these regions illustrate the need to improve the ability to quantify watershed nitrogen saturation rates. Until watershed nitrogen saturation is better understood, significant uncertainty will continue to accompany surface water benefits analyses of potential reductions in sulfur and nitrogen deposition. Despite the uncertainty, however, it is useful to recognize that any reductions in nitrogen deposition would not only reduce total acidic deposition rates, but also reduce the actual times to watershed nitrogen saturation. This process is similar to the ongoing process whereby reductions in sulfur deposition due to the 1990 CAAA are likely extending times for water sulfur saturation within watersheds.

2.5.4 Overview of International and State Acidic Deposition Criteria and Standards

International consideration of ecologically based standards to address air pollution problems originated in the mid-1960s. Driven primarily by the acid rain debate over the next 30 years, the original concept of using concentration-based criteria gave way to using uniform maximum allowable mass deposition rates, with 20 kg-wet SO_4^{2-}/ha/yr (6.7 kg-S/ha/yr) being the first widely recognized interim target load. Subsequently, site-specific critical loads were increasingly emphasized. Their development is generally attributed to Swedish research efforts in the late 1960s.[39]

Critical loads are estimates of the maximum pollutant loadings that environmental resources can absorb on a sustained basis without experiencing measurable degradation. Only inherent ecological properties are included in site-specific critical load determinations. Steps involved in defining and implementing critical loads usually include (1) resource identification and characterization, (2) identification of regions or functional subregions, (3) characterization of deposition within subregions, (4) definition of assessment endpoint(s) (see below), (5) selection and application of models, and (6) mapping projected environmental responses.[40]

---

[39] Nilsson, J. and P. Grennfelt (editors). 1988. Critical Loads for Sulphur and Nitrogen Report from a Workshop Held at Skokoster, Sweden, 19-24 March 1988, UN/ECE and Nordic Council of Ministers.

[40] Strickland, T.C., G.R. Holdren, Jr., P.L. Ringold, D. Bernard, K. Smythe, and W. Fallon. 1993. A National Critical Loads Framework for Atmospheric (continued)

Target loads differ from critical loads in that their definitions incorporate social, policy, economic, and related considerations along with scientific findings. An example of a target load would be an acidic deposition level adequate to maintain proportions of ANC≤50 μeq/l waters at or below the proportions found during the 1984-85 NSWS for one or more of the surveyed regions. (This example is illustrated in Section 3.6.) Other possible target loads could include, for example, a deposition level to produce a specified percentage reduction in the 1984-85 proportions of ANC≤50 μeq/l waters.

Assessment endpoints are formal expressions of the environmental value(s) to be protected. They can include thresholds for "deleterious conditions" (commonly some adverse ecological condition) that a standard would attempt to prevent. Assessment endpoints should be biologically relevant, operationally definable, accessible to prediction and measurement, and sensitive to the pollutant(s) of concern. From a policy perspective, assessment endpoints also should be socially relevant; that is, they should be environmental characteristics mutually understood and valued by the public and by decision makers (e.g., populations of crops, trees, fish, birds, or mammals). When the most appropriate sensitive species or other endpoint used is not socially valued, then their link to valued species or other valued environmental attributes should be explicitly demonstrated to simplify understanding of why using such an endpoint is useful. Using endpoints that have social relevancy helps to unify scientific and social concerns in commonly shared objectives.

The first and still dominant ecological assessment endpoint used for critical and target load estimation is freshwater aquatic responses, most commonly manifested as changes in pH or ANC. Of particular interest here is that pH or ANC changes themselves are often a relatively minor concern, but the influence of such changes on biological species is of considerable importance. Therein is a defining attribute of how the concept of critical loads has developed in its international use, i.e., critical loads of chemicals (e.g., SO_4^{2-} and NO_3^-) are surrogates for biological concerns. The key biological concern most often focused upon is fish viability.

Deposition Effects Assessment: I. Method Summary. *Environmental Management* 17:329-324.

A critical load value can be viewed as a single, especially important point along a continuous range of values representing an ecological loss or damage function. Viewing a critical load as part of an ecological loss function is especially important because that view has shaped much of the European debate over the appropriate and scientifically defensible uses of critical loads in acid rain control policy development. Further, these loss functions are particularly important when it is recognized (as it has been in Europe, Canada, and the United States) that significant numbers of highly sensitive receptor locations have associated critical loads that likely cannot be met, even with widespread and high levels of acidic deposition reduction employing the limits of technological feasibility. Loss functions provide a mechanism to aggregate ecological damage across regions and integrate a quantitative understanding of acidic deposition to ecological damage relationships. Without these functions, more qualitative, often highly subjective, aggregation approaches are used to place critical load concepts into policy-relevant contexts. The results of such approaches most often are termed target loads, as described above.

Most countries of western Europe have adopted the system for estimating critical loads developed by the Coordination Center for Effects (CCE) of the United Nations Economic Commission for Europe (UNECE) under the auspices of the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP) (Exhibit 15). A recently published manual presents improved methods that are being widely applied across Europe for mapping both critical loads to protect sensitive resources and critical levels of allowable atmospheric concentrations of acidic pollutants.[41] In this system, critical loads are developed for individual cells of the mapping grid based on the potential sensitivity to acidification of forest soils and surface waters. Critical loads for sulfur, nitrogen, and total acidity have been mapped across Europe. Although a variety of models were used, nearly all countries that participated in the European mapping effort employed the simple mass balance steady-state method as the underlying approach to estimate critical loads. Several countries also used dynamic models and other methods. In the CCE approach,

[41] Task Force on Mapping. 1993. *Manual on Mapping Critical Levels/Loads.* Coordination Center for Effects, U.N. Economic Commission for Europe. Berlin, Germany.

EXHIBIT 15. LRTAP

In 1981, the United States became party to the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP). Signatory countries include most western European countries, several newly Independent States, Canada, and the United States. The Convention symbolizes a formal recognition on the part of signatory countries that the transboundary flow of air pollution is an important issue that merits formal international cooperation. In 1985, the first Sulfur Protocol under the Convention committed those countries who signed to a 30 percent reduction in emissions of sulfur dioxide from 1980 levels. (The United States did not sign based on significant sulfur dioxide emission reduction efforts already undertaken in the 1970s.) Soon thereafter, emissions reductions based on achievement of critical loads became the focus of efforts under LRTAP. In 1994, most countries signed the Second Sulfur Protocol requiring mapping of critical loads for all affected countries. It is the expectation that this effort will lead to emission reductions based on the critical loads. A Nitrogen Oxide Protocol was signed in 1988 by most countries, including the United States. The NO_x Protocol outlined steps to reduce national annual NO_x emissions. It also initiated research and cooperative efforts on critical loads for nitrogen.

the indicator used to estimate critical loads for forest soils (using the simple mass balance steady-state model) is the concentration of aluminum in the soil solution required to maintain pH above 4.0. Some countries varied the basis for their mapping procedures based on the availability of the data collected by the individual countries, and the regional and national concerns regarding the sensitivity of specific sensitive resources. The majority of critical load values in Europe reflect the sensitivity of forest soils. Critical loads in Finland, Norway, Sweden, Switzerland, and several of the newly Independent States reflect forests and surface waters.[42]

The single most important technical attribute around which European activities on acid deposition standards have revolved is associated with defining the spatial resolution used. Interestingly, the early decision to use a 150 km by 150 km square grid as the fundamental spatial assessment unit for acidic deposition control strategies had no direct connection to spatial levels of resolution deemed appropriate for critical load estimation. In fact, the grid was in place well before the critical loads concept achieved common usage. This relatively coarse grid size, however, often allows for significant spatial variation in environmental types and designated critical load alternatives within individual cells. This leads to difficult questions regarding spatial estimation of specific critical loads appropriate for supporting deposition-based control policy and measurement of maintenance and/or exceedance levels.

To provide a reasonable level of protection for more sensitive ecological resources within each grid cell, the European approach uses cumulative distributions of critical load values and selects from this distribution a non-exceedance level for each cell. Under this approach two loadings are calculated: one that would protect 95 percent of sensitive ecological resources within the grid (i.e., the 5-percentile load), and one that would protect 99 percent of the resources (i.e., the 1-percentile load). This procedure reconciles some of the basic problems that arise when point estimates are used to represent regional concerns. But the approach still holds difficulties related largely to the process of selecting appropriate critical load values from the resulting distribution functions. Specifically, it is sometimes difficult to determine the rationale by which individual critical load values are selected among the different cells. Qualitative considerations, which often stem from political agreements, also have a role in this process.[43] Despite the different sensitivities of various ecosystems, most critical loads developed in Europe are very low when compared to present deposition. This has given some countries the impetus to seek greater emissions reductions than were already planned. Thus, most of the reductions of sulfur emissions

[42] Coordination Center for Effects, National Institute of Public Health and Environmental Protection. 1991. (continued)

Mapping Critical Loads for Europe. CCE Technical Report No. 1. U.N. Economic Commission for Europe, Bilthoven, Netherlands.

[43] Henriksen, A., and D.F. Brakke. 1988. Sulfate deposition to surface waters. *Environmental Science and Technology* 22(1):8-14.

under the second Sulfur Protocol fall in the range of 50–80 percent. The European community as a whole is projecting emissions decreases of over 60 percent by the year 200 compared to 1980 levels. The four European countries that signed the second Sulfur Protocol and their commitments to reductions (relative to 1980) are:[44]

- France: 74% by 2000; 78% by 2010
- Germany: 83% by 2000; 87% by 2005
- Italy: 65% by 2000; 73% by 2005
- United Kingdom: 50% by 2000; 80% by 2010

The French reductions translate into an emissions level of approximately 825,000 tons of sulfur dioxide; emissions reductions in the other three countries are around 1.1 million tons. These emissions reductions will occur in an area that is in general much less energy intensive than in the two North American members of LRTAP (the United States and Canada), so it is difficult to argue that the Europeans are simply getting easy, low-cost reductions. Taken together, these four European industrialized countries represent a population very close to that of the United States. By 2010, their emissions of sulfur dioxide will be less than 5 million tons, while the United States is projected to have emissions of around 15 million short tons. Canada committed to reducing its emissions by 46 percent within a Sulfur Oxide Management Area (SOMA), which represents a targeted approach to the acidification problem in Eastern Canada. Canada's population is about 10 percent that of the United States; it is committed to a national cap of 3.2 million metric tons (about 3.5 million short tons) in the year 2000.

Canada adopted 6.7 kg-S/ha/yr (wet deposition) in the early 1980s as what would now be termed a *target load.* This value was based on available data indicating that loss of sport fish would occur at pH less than 5.3, and this loss would produce significant economic and social impacts. This target load was not, however, intended to protect extremely sensitive areas. Canadian policy makers concluded that additional research was necessary to determine appropriate loading limits to completely protect all sensitive Canadian ecological resources. The target load was used as a goal in developing the Canadian acid rain control program and in discussions with the United States on transboundary air pollution. As a result of current U.S. and Canadian acid rain control programs, most areas of Canada are expected to reach the 6.7 kg-S/ha/yr target.

Subsequently, in 1990, critical loads for watersheds in eastern Canada were calculated using steady-state water chemistry models that projected sulfur deposition necessary to maintain 95 percent of the lakes at pH 6.0 or greater.[45] Included in this approach were allowances for maintaining conditions in naturally acidic surface waters. Resulting critical load estimates ranged from less than 2.7 to more than 6.7 kg-wet S/ha/yr, with the variation primarily dependent on geological characteristics. The eastern region of Canada, including the Atlantic provinces, Labrador, and eastern Quebec, was determined to require the lowest critical loads (less than 2.7 kg-S/ha/yr), which are close to background deposition levels. Critical loads estimated for Quebec ranged from 3 to more than 6.7 kg-S/ha/yr, and for Ontario they ranged from 2.7 to more than 6.7 kg-S/ha/yr. In a separate analysis, a simple mass balance approach was used to determine that a loading of 5 to 6.7 kg-S/ha/yr wet deposition would maintain surface water pH greater than 5.3 on an annual basis in watersheds that have lakes with ANCs of 200 μeq/l or greater in regions of low runoff.

Using the initial Canadian effort as an example, the New England states and New York adopted Canada's first target load of 6.7 kg-S/ha/yr (wet deposition) as a level adequate to protect moderately sensitive ecological resources from additional damage caused by acidic deposition.[46] This level was not viewed, however, as adequate to protect the most sensitive resources within these regions.

---

[44] United Nations Economic Commission for Europe. 1994. *Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulphur Emissions.* ECE/EB,AIR/40. Geneva.

[45] Federal/Provincial Research and Monitoring Coordination Committee. 1990. *The 1990 Canadian Long-Range Transport of Air Pollutants and Acid Deposition Assessment Report.* 8 parts. Research and Monitoring Coordination Committee, Canada.

[46] New England Governor's Conference. 1985. *History and the Development of the New England Position on Acid Rain.* New England Governor's Conference, Inc.

New York State Department of Environmental Conservation (NYSDEC). 1985. *A Policy for New York State to Reduce Sulfur Dioxide Emissions: The Sulfur Deposition Control Program.* Final Environmental Impact Statement. NYSDEC, Albany, NY.

Maryland developed critical loads based on the sensitivity of individual streams to acidification.[47] This effort included as its overall goal an assessment of the extent to which the state could meet or surpass its ecological objectives to minimize potential acidic deposition effects. Calculated critical loads for areas within Maryland ranged by region from less than 8 to more than 64 kg-S/ha/yr. These loads were developed using (1) two models (PROFILE and MAGIC), (2) pH limits required to protect the most sensitive life stages of biological indicator species, and (3) a complex of specific physical, chemical, and biological factors that potentially affect soil and water chemistries. Acid sensitivities for three indicator fish species were used across the different regions assessed: blueback herring (pH=6.2), smallmouth bass (pH=5.8), and brook trout (pH=5.75). The assessment revealed that critical loads at several sensitive receptor locations could not be met for any plausible emissions control scenario. These locations were thus deemed possible candidates for site-specific mitigation measures, principally stream liming.

Minnesota is the only state with an established deposition standard for sensitive areas.[48] Sensitive areas are defined based on lake ANC, with the state's deposition standard of 3.7 kg-S/ha/yr (wet deposition) established to protect lakes whose ANC is less than 40 μeq/l. The standard was derived using regression techniques to relate deposition SO_4^{2-} concentrations and acidity to the ability of sensitive Minnesota lakes (ANC<40 μeq/l) to assimilate additional acid loadings. This deposition standard may also be viewed as equivalent to the critical load for this region because maps of sensitive soils show that the majority of areas with potentially the most sensitive soils correspond to those regions with sensitive lakes.

In contrast to regions east of the Mississippi River, deposition of nitrogen has long been viewed as a more significant problem than deposition of SO_2 in much of the western United States. For example, NO_3^- approximately equals SO_4^{2-} deposition in some areas of California. Consequently, critical loads for nitrogen deposition have been estimated for California,[49] but similar loads for sulfur have not. Studies show that loadings of 10 to 20 kg-N/ha/yr would likely protect California forests. Critical loadings recommended to protect sensitive California resources ranged from 5 to 45 kg-N/ha/yr, depending on the region. Other state efforts are currently underway.

2.5.5 Spatial and Temporal Issues in Development of a Standard

Information discussed in Sections 2.3, 2.4, 2.5.2, and 2.5.3 clearly demonstrate that regions of North America differ in both their potential sensitivity and risk to adverse effects caused by sulfur and nitrogen deposition. These differences provide a strong scientific justification for setting different standards that recognize variations among and within sensitive regions. Regions covered by any individual standard would be larger than most states and undoubtedly smaller than the nation as a whole. It is also clear that appropriate and scientifically justifiable environmental goals could differ across areas within individual states.

Sensitive resources tend to cluster within relatively easily defined geographic areas often associated with specific mountain ranges and other areas having relatively unique geologic attributes. Potential protection requirements for ecological resources in sensitive regions can be identified, categorized, and aggregated across several levels of organization. These include regions, landscapes, ecosystems, communities, populations, and individual site-specific measures (e.g., critical stream habitat for a listed endangered fish species). In general, the smaller the area of concern, the greater the precision required in establishing the basis for standards and in determining the boundaries where standards would apply. Under a critical loads approach, appropriate ecological rationales would need to be developed for whatever scale is targeted for protection by a standard. Furthermore, there is significant variation in spatial scale of exposure (i.e., wet and dry deposition) on a regional as well as site-specific level. Deposition and effects monitoring (further described in the following

[47] Sverdrup, H., P. Warfvinge, M. Rabenhorst, A. Janicki, R. Morgan, and M. Bowman. 1992. Critical Loads and Steady-State Chemistry for Streams in Maryland. *Environmental Pollution* 77:195-203.

[48] Minnesota Pollution Control Agency. 1985. *Statement of Need and Reasonableness: Proposed Acid Deposition Standard and Control Plan.* State of Minnesota Pollution Control Agency, St. Paul, MN.

[49] Takemoto, B.K., M. Bergen, N. Motallebi, M. Mueller, H. Margolis, and S. Prasad. 1992. *The Atmospheric Acidity Protection Program: Annual Report to the Governor and Legislature.* Draft report. State of California Air Resources Board, Research Division, Sacramento, CA.

chapter) is an essential component in the standard setting and implementing process.

Beyond these considerations regarding differences in the spatial scale are important considerations regarding the temporal scale. For example, the potential for exposure to, and risk from, acidic conditions is often highest during the spring due to the mobilization of the winter accumulations of deposited acids and the activation of seasonal biological growth process. Also, the sensitivity of many resources changes over time. For example, the most sensitive life stages of many fish species are hatching eggs and newly hatched fry. The periods of greatest sensitivity for many species are spring and fall when most fish species hatch. Similarly, spring budding periods for flowers and leaves and initial root growth by seedlings are particularly sensitive periods for many terrestrial plants. In contrast, many resources have low sensitivity during the winter, when their biological activity is low. Patterns in weather variations may change from year to year and would also have to be considered in a standard-setting process. Options that could be evaluated for appropriate averaging periods which accommodate temporal issues include single-event loadings, seasonal loadings, total annual loadings, average annual loadings, 10-year average loadings and 50-year average loadings. The timing of a standard, therefore, ultimately has significant implications for development and implementation of an acid deposition standard.

Determining appropriate averaging periods must also include consideration of possible temporally delayed effects. For example, the chemistry of spring meltwaters may better reflect accumulated winter deposition than springtime deposition. Such processes could indicate the need in some regions for more stringent winter deposition standards. Such standards might aim to minimize over-winter accumulations of strong-acid anions in snow packs, thereby minimizing the potential acidity of spring meltwaters and their potential adverse effects on receiving waters. Likewise, in those areas where episodic pulses of nitrogen are the primary concern, temporal considerations may best be focused on a particular pollutant. Consideration of effects that are cumulative in nature and potentially significantly delayed in time is a complex yet critical component in the development of an acid deposition standard.

2.6 CONTROLLING SULFUR AND NITROGEN TO REDUCE SURFACE WATER ACIDIFICATION

Atmospheric deposition of sulfur- and nitrogen-containing compounds, primarily SO_4^{2-} and NO_3^-, contributes to the acidic deposition problem, as reviewed in Section 2.2.1. The relative contribution of sulfur and nitrogen to this problem differs among regions, depending not only on external differences in the deposition rates of these chemicals, but also on differences among the capacity of receptor watersheds to retain sulfur and nitrogen, as discussed in Sections 2.2.1, 2.5.2, and 2.5.3. Such differences have led some authorities (e.g., those in California) to date to focus solely on the need to control nitrogen deposition (see Section 2.5.4) while others have focused primarily on sulfur.

For most regions of North America affected by and at risk from chronic effects of acidic deposition, the principal present concern is sulfur deposition. As more fully discussed in Sections 2.2.1, 2.5.2, and 2.5.3, sulfur deposition appears to be the primary cause of long-term chronic acidification in all affected sensitive areas. The NBS illustrates that for the near term sulfur deposition is likely to remain the overriding acidification problem in most sensitive areas of eastern North America. This likely will remain the case until annual retention of nitrogen decreases sufficiently and the full potential acidifying influence of nitrogen deposition commences. At these times, sulfur and nitrogen are projected to have approximately equal roles in surface water acidification. Thus, for most areas, where current or near-term needs for additional acidic deposition control are projected, and where watershed nitrogen saturation is not likely imminent, the greatest potential benefits will come primarily from control of sulfur emissions and deposition.

A significant and growing body of scientific research indicates, however, that nitrogen deposition is a major and important contributor to the acidic deposition problem. First, many areas of the West are more affected by nitrogen deposition than by sulfur deposition. Second, as briefly reviewed in Section 2.2.1, nitrogen (in the form of nitrate anion) frequently has been found to be a significant contributor to episodic events in streams and lakes in some parts of the Northeast.[50] In these areas, as

[50] This does not imply that sulfur deposition is not often a key component of episodic acidification, because sulfur has often been found to be the primary cause

(continued)

adverse effects accompanying chronic acidification due to sulfur deposition are reduced, overall adverse effects due to episodic acidification would likely continue to impair the water quality in many of these surface waters, but the extent of these effects would likely be reduced because reducing the chronic sulfur effects also decreases potential episodic effects as well. Third, some watersheds of the Northeast (e.g., in the Catskill Mountains of New York) and the mid-Appalachians may be moving toward nitrogen saturation. For these regions, nitrogen deposition is now or would likely become a more direct cause of chronically acidic conditions in sensitive waters, with potential adverse effects caused by acidic sulfur and nitrogen deposition becoming approximately equal and directly additive. In fact, additional limits on nitrogen deposition would likely produce a two-fold potential benefit by both reducing acidic deposition rates and lengthening average times to watershed nitrogen saturation. These benefits would effectively allow a greater mass of NO_3^- to be deposited over longer periods without significantly increasing surface water acidification processes.

Scientific uncertainties regarding regional rates and differences in processes affecting watershed assimilation of acid-forming sulfur and nitrogen compounds preclude defining either national or regional protection levels below which deposition of either chemical would produce no adverse impact. Available information does indicate, however, that additional deposition reduction throughout the range of potential reductions in sulfur and/or nitrogen depositions down to background deposition loads would likely reduce regional proportions of chronically acidic surface waters (ANC ≤0 μeq/l) or proportions of surface waters potentially most sensitive to episodic effects (ANC≤50 μeq/l) or proportions of both groups. The magnitude of these potential benefits to each group of surface waters varies considerably by region. NBS projections indicate for some regional surface water groupings that potential benefits may amount to a few percentage points shift in proportions of acidic or sensitive surface waters benefiting, while for other groupings in other regions potential benefits from deposition reductions could benefit 20 percent or more of the acidic or sensitive waters. Note, however, that even a few percentage points may mean many lakes or stream reaches. Now, however, even a sound qualitative ranking of these differences awaits resolution of key scientific unknowns, exemplified by the marked uncertainty associated with quantifying regional differences in their remaining times to watershed nitrogen saturation.

of episodic acidification in areas both within and outside the Northeast. For example, see A.K. O'Brien, K.C. Rice, M.M. Kennedy, and O.P. Bricker. 1993. Comparison of episodic acidification of mid-Atlantic upland and coastal plain streams. *Water Resources Research* 29(9):3029-3039.

CHAPTER 3

SOURCE-RECEPTOR RELATIONSHIPS AND DEPOSITION REDUCTIONS UNDER VARIOUS EMISSIONS SCENARIOS

3.1 INTRODUCTION

Acidic deposition results from a complex series of interactions among chemical compounds present in the atmosphere. The two most important groups of chemicals are sulfur- and nitrogen-containing compounds. These chemicals are emitted to the atmosphere from natural and anthropogenic sources, with anthropogenic sources dominating. Natural sources include vegetative emissions, geothermal activities, forest fires, lightning, soil, and salt-water organisms. Anthropogenic sources include point sources such as utilities, industrial boilers and other industrial processes, mobile sources including automobiles, trucks, and off-highway vehicles, and area sources such as residential boilers which are too small and numerous to track individually.

Sulfur and nitrogen compounds in the atmosphere can be transported hundreds to thousands of kilometers by meteorological forces. During transport sulfur dioxide (SO_2) and nitrogen oxides (NO_x), the primary emissions of these species, are oxidized in the air or in cloud-water to form other, secondary compounds. The great majority of these compounds, particularly sulfate and nitrate, are acidic. The oxidizers, such as the hydroxyl radical, hydrogen peroxide, and ozone are produced by reactions of volatile organic compounds (VOC) and NO_x. The sulfur and nitrogen pollutants are deposited to the earth by either dry or wet deposition. Dry deposition occurs when particles settle out of the air onto the earth or when gases or fine particles directly impact land, plants, or water, or when plant stomata take up gases, such as SO_2. In wet deposition, pollutants are removed from the atmosphere by rain or snow. Fine particles or secondary aerosols formed by these same processes scatter or absorb visible light and thus impair visibility. When inhaled these secondary aerosols and their gaseous precursors can also cause adverse human health effects. Potential benefits to visibility, human health, materials, and cultural resources from controlling acidic deposition are discussed in Chapter 4.

The complex relationship between emissions and deposition depends on a large number of physical, chemical, and biological processes. To understand the environmental impact of the CAAA and to develop and analyze strategies to reduce the effects of acidic deposition, the relationship between emissions and deposition must be understood not only for the present, but also for future years. To predict deposition a model must be able to describe the transformation of anthropogenic and biogenic emissions by atmospheric processes to wet and dry deposition. The goal of deposition modeling is to simulate the source-receptor relationships that translate emissions into deposition values in space and over time. An understanding of these complex interactions is necessary to develop a comprehensive approach to achieving the environmental goals discussed in Chapter 2.

This chapter addresses the following requirement of Section 404 (Appendix B) of Title IV of the CAAA:

- *Description of the state of knowledge with respect to source-receptor relationships necessary to develop a control program on such standard or standards and additional research that is on-going or would be needed to make such a control program feasible*

Section 3.2 describes state-of-the-art atmospheric modeling techniques, the uncertainties associated with predictive modeling, precursor emissions and emissions inventories, and deposition species. This section describes RADM, the atmospheric model used for this study, and examines its use in modeling of acidic deposition and the results of its evaluation.

Section 3.3 presents RADM results that explore and define source-receptor relationships. Relationships prior to implementation of the 1990 CAAA are compared and contrasted to those expected after full implementation of the Act in 2010. The model discussion is followed in Section 3.4 by a description of the inventories used to evaluate alternative emissions control scenarios.

In Section 3.5, source-receptor relationships from RADM are used to assess the environmental impact of the CAAA and to predict deposition values for acidic sulfur and nitrogen under various alternative emissions scenarios for the year 2010. Emissions scenarios analyzed include full implementation of Title IV with trading, full implementation of Title IV without trading, national reductions in utility and industrial SO_2 emissions beyond Title IV, and national reductions in utility and industrial NO_x emissions beyond Title IV. Regionally targeted emissions reductions for SO_2 are examined in Section 3.6.

3.2 THE REGIONAL ACID DEPOSITION MODEL

RADM has been developed over the past 10 years under the auspices of the National Acid Precipitation Assessment Program (NAPAP) to address policy and technical issues associated with acidic deposition. The model is designed to provide a scientific basis for predicting changes in deposition resulting from changes in precursor emissions, to predict the influence of emissions sources in one region on acidic deposition in other geographic regions, and to predict the levels of acidic deposition in certain sensitive receptor regions.

A key requirement for the model selected for NAPAP was the ability to assess changes in sulfate in response to projected changes in SO_2 emissions. Based on knowledge gained from models and experimental measurements, a reduction in SO_2 emissions is expected to lead to a less than equivalent reduction in sulfate deposition. This nonequivalency between emissions reductions and decreases in deposition is due to the nonuniform spatial distribution of emissions reductions and the complexities of atmospheric chemistry. While simpler models can predict the nonequivalency due to spatial nonuniformities, a complex model such as RADM is needed to calculate the additional affects of atmospheric chemistry on deposition.

The development, application, and evaluation of RADM has been documented extensively by NAPAP.[51,52,53] RADM continues to undergo periodic peer reviews, evaluations, and improvements.[54,55,56] Understanding and modeling acidic deposition requires consideration of a complex range of physical and chemical processes and their interactions, including:

- The emissions of precursor chemicals that produce and regulate acidity in atmospheric deposition;
- The meteorological processes that transport and mix emitted species in space and time;
- The physical and chemical transformations that alter the physical phases and chemical properties of emitted species;
- The meteorological factors and properties of the Earth's surface that lead to deposition of acidic substances.

RADM is an Eulerian model in which concentrations of gaseous and particulate species are calculated for specific fixed positions in space (grid cells) as a function of time. The concentration of a specific pollutant in a grid cell at a specified time is determined by: the emissions input rate; the transport of that species by wind into and out of the grid in three dimensions; movement by turbulent motion of the atmosphere; chemical reactions that either produce or deplete the chemical; the change in concentration due to vertical transport by clouds; aqueous chemical transformation and

[51] Renne, D., et al. December 1989. *Models Planned for Use in the NAPAP Integrated Assessment. Section 4: Atmospheric Models.* National Acid Precipitation Assessment Program.

[52] Chang, J.S., P.B. Middleton, W.R. Stockwell, C.J. Walcek, J.E. Pleim, H.H. Lansford, F.S. Binkowski, (continued)

S. Madronich, N.L. Seaman, and D.R. Stauffer. December 1990. *The Regional Acid Deposition Model and Engineering Model.* SOS/T Report 4. In: Acidic Deposition: State of Science and Technology. National Acid Precipitation Assessment Program.

[53] Dennis, R.L., W.R. Barchet, T.L. Clark, and S.K. Seilkop. September 1990. *Evaluation of Regional Acid Deposition Models (Part I). SOS/T* Report 5. In: Acidic Deposition: State of Science and Technology. National Acid Precipitation Assessment Program.

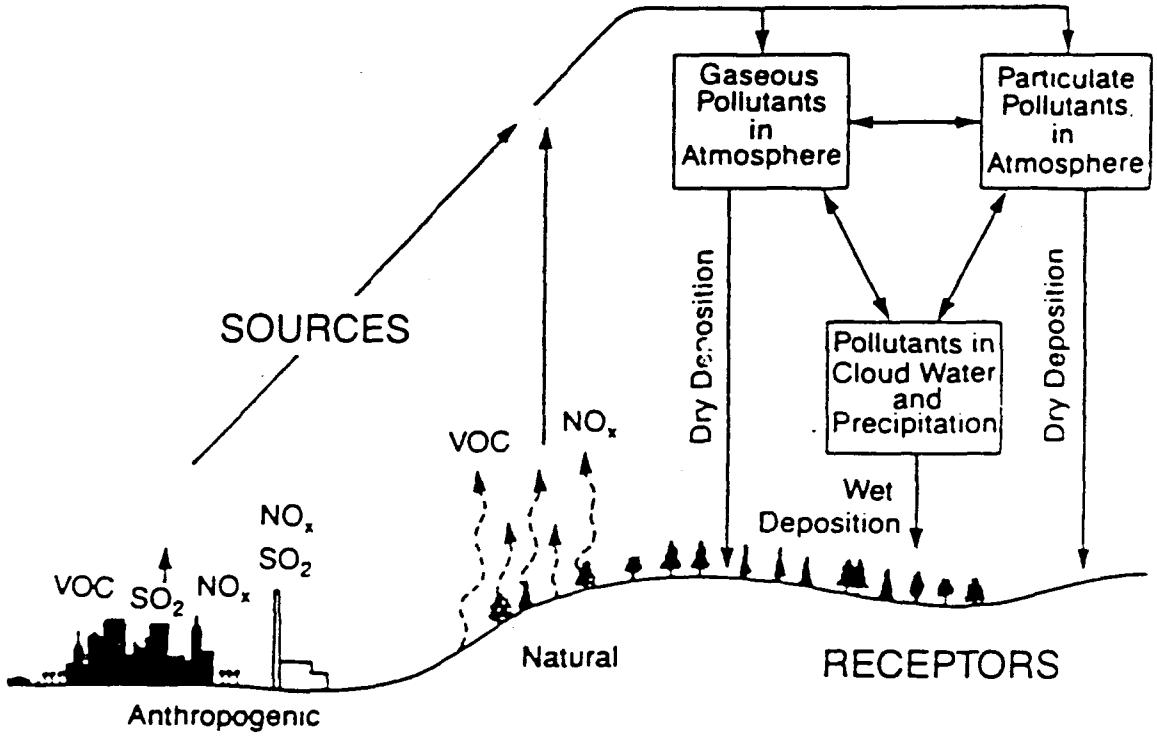
[54] Dennis, R.L., J.N. McHenry, W.R. Barchet, F.S. Binkowski, and D.W. Byun. 1993. Correcting RADM's sulfate underprediction: Discovery and correction of model errors and testing the corrections through comparisons against field data. *Atmospheric Environment* 27A(6):975–997.

[55] McHenry, J.N., and R.L. Dennis. 1994. The relative importance of oxidation pathways and clouds to atmospheric ambient sulfate production as predicted by the Regional Acid Deposition Model. *Journal of Applied Meteorology* 33(7):890–905.

[56] External Review Panel report on RADM evaluation for the Eulerian Model Evaluation Field Study Program.

scavenging; and removal by dry deposition. These physical and chemical process are depicted in Exhibit 16.

EXHIBIT 16. PHYSICAL AND CHEMICAL PROCESSES CONTRIBUTING TO ACIDIC DEPOSITION

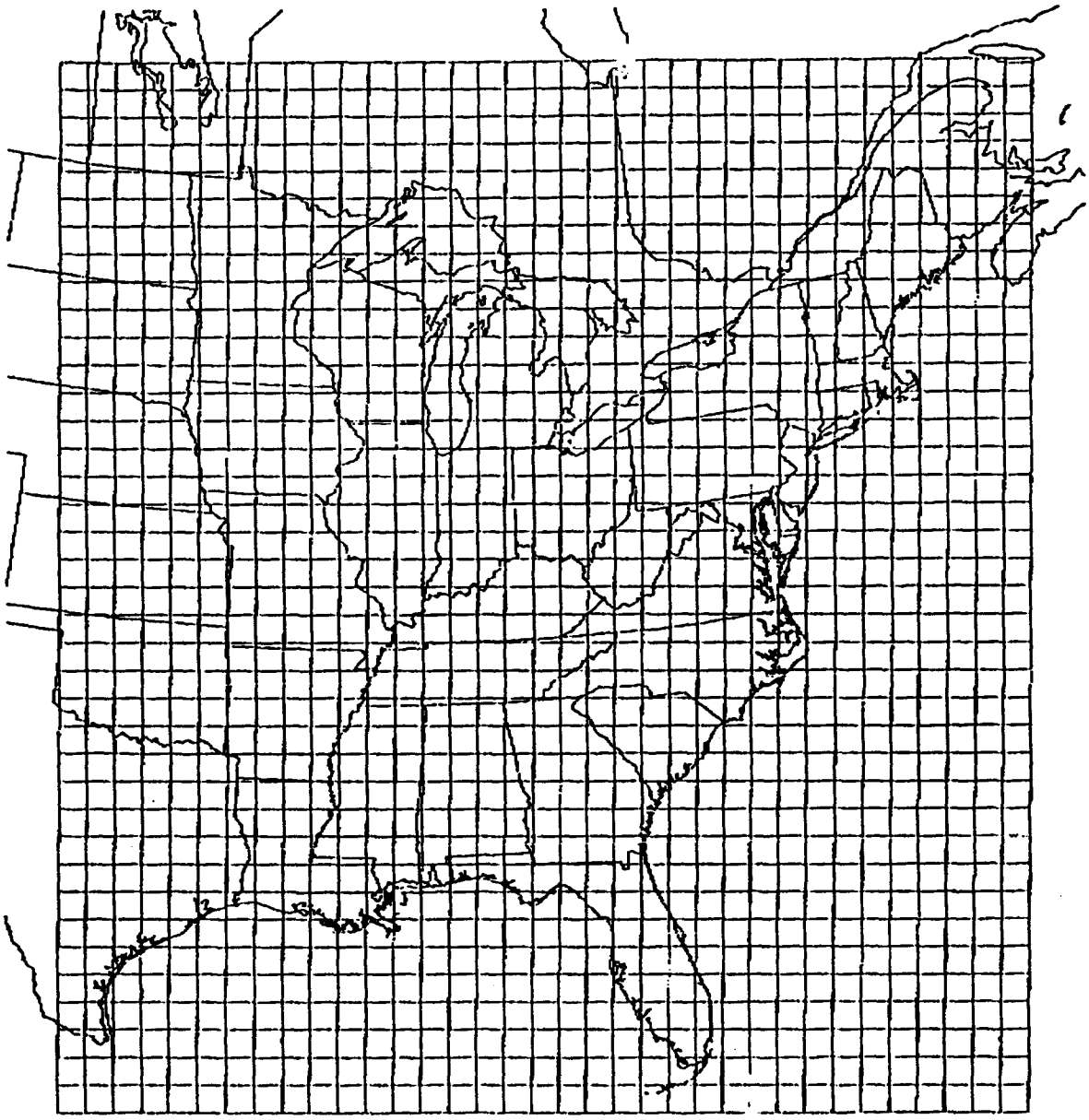


The version of RADM used for NAPAP and for the analyses presented in this report covers an area of 2,800 by 3,040 km east of central Texas and south of James Bay, Canada to the southern tip of Florida. RADM divides this area into 80 by 80 km grid cells. For sulfur deposition modeling the distance from ground level to 16 km in altitude was resolved into 6 vertical layers; for nitrogen deposition 15 layers were used. The RADM domain, pictured in Exhibit 17, consists of 35 by 38 horizontal grid cells. The model is run with either 7,980 or 19,950 cells depending upon whether 6 or 15 vertical layers are employed. For each grid cell, predictions are generated at dynamically determined time-steps of seconds to minutes and are output hourly by RADM with 41 chemical species being transported. Hourly wet and dry deposition values are also generated for each surface cell for 12 species (6 wet and 6 dry).

The meteorological fields used to drive the RADM are from the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM4). The MM4 is run using 4-dimensional data assimilation (4DDA) to produce the most accurate recreation of past weather.[57] An aggregation technique, described fully by Dennis et al.,[53] developed during NAPAP is used to develop annual estimates of acidic deposition. Meteorological cases with similar wind flow patterns were grouped by applying cluster analysis to classify the wind flow patterns from 1982 to 1985, resulting in 19 sampling groups, or strata. Meteorological cases were randomly selected from each stratum; the number selected was based on the number of wind flow patterns in that stratum relative to the number of patterns in each of the other strata, to approximate proportionate sampling. A total of 30 cases were used in the current aggregation approach. Deposition results for these cases were weighted according to the strata sampling frequencies to form annual averages.

[57] Seaman, N.L., and D.R. Stauffer. 1989. *Development of Four-Dimensional Data Assimilation for Regional Dynamic Modeling Studies.* Final Report to the U.S. Environmental Protection Agency, Contract CR-814068-01, the Pennsylvania State University, 102 pp.

EXHIBIT 17. THE RADM MODELING DOMAIN



Development and implementation of an acidic deposition control strategy requires an understanding of the interaction among emissions of several chemical species, the spatial and temporal patterns of those emissions, and atmospheric transport of those species to regions where deposition occurs. It is important, therefore, to understand the uncertainty and reliability of model predictions. The following subsections briefly describe the key input and functional components upon which RADM predictions are based. The discussion on emissions and atmospheric chemistry explains why certain emissions are important, distinguishes anthropogenic (controllable) from natural (background sources), and describes why detailed spatially and temporally resolved emissions inventories are needed to accurately predict deposition. Subsections 3.2.2 and 3.2.3 describe the development of source-receptor relationships and how these relationships can be used to identify emissions sources responsible for deposition, whether proximate or hundreds of kilometers distant. The reliability and

confidence of the scientific community in using modeling results for decision-making is discussed in subsection 3.2.4.

3.2.1 Emissions and Atmospheric Chemistry

The principal acids in deposition are sulfuric (H_2SO_4) and nitric (HNO_3) acids. Thus, emissions of compounds containing sulfur and nitrogen have received primary emphasis in acidic deposition control strategies. However, emissions of VOCs and their oxidation products are extremely important because they are involved in reactions that produce the oxidizing species that lead to formation of sulfuric and nitric acids in the atmosphere. Key environmentally important species predicted by RADM are:

- AMBIENT CONCENTRATIONS: SO_2, NO, NO_2, HNO_3, O_3, H_2O_2, NH_3, PAN, HCHO, CO, aerosol SO_4^{2-}
- WET DEPOSITION: SO_4^{2-}, NO_3^- as HNO_3, NH_3, H^+
- DRY DEPOSITION: SO_2, SO_4^{2-}, HNO_3, O_3, NO_2

The RADM chemistry component consists of 140 reactions among 60 species, 40 of which are organic compounds. Chemical decomposition by solar radiation (photolysis) is included in the model chemistry as are aqueous-phase reactions which occur in clouds. These latter reactions are particularly important in sulfuric acid formation. The chemically derived nonequivalency between emissions reduction and deposition decreases is due in part to local depletion of hydrogen peroxide, a compound produced by atmospheric photochemical (involving sunlight) reactions that is important in the oxidation of aqueous-phase SO_2 to sulfate.[58] This nonlinear oxidant limitation affects only wet deposition of sulfate. Details of the RADM chemistry are described in NAPAP State of Science and Technology Report 4.[52]

Inputs to RADM include hourly emissions of SO_2, sulfate, nitric oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), carbon monoxide (CO), particulate matter, and 15 classes of VOCs from natural and anthropogenic sources. Emissions inventories used for RADM were derived from the 1985 NAPAP Emissions Inventory, the most comprehensive, highest quality air emissions inventory ever assembled. (RADM inputs have since been updated to include more recent sector-specific inventories such as the National Allowance Data Base developed under the Acid Rain Program for utility emissions.) The basis and key assumptions for the 1985 NAPAP Emissions Inventory are described below. A detailed description of this inventory and the data processing for use in RADM are described in NAPAP State of Science and Technology Report 1.[59]

Natural Emissions Sources

Natural emissions of acidic precursor species, organic matter, and alkaline materials (dust) are generated by vegetative matter, microbes, geothermal activity, natural combustion (such as forest fires), lightning, and salt-water organisms. These sources, in contrast to anthropogenic sources, are widely distributed, small, sporadic, and subject to large seasonal and weather-related variations. Total VOC emissions from biogenic sources are estimated to be of the same order of magnitude as VOC emissions from anthropogenic sources.[60] Principal biogenic sources are trees, shrubs, grasses, agricultural crops, decaying leaf litter, and vegetation in fresh and salt water. Some biogenic compounds are very reactive in the atmosphere; others are relatively inert. Emissions for individual grid cells and specific VOCs or VOC classes are calculated from estimates of biomass data (vegetation type, species, land-use coverage, and leaf area index), adjusted for seasonal variation, temperature, solar intensity, soil conditions including moisture, and elevation.

Natural emissions of SO_2, sulfates, and nitrogen oxide have been found to be less important than anthropogenic sources. Natural emissions of sulfur, which are not well understood, are estimated to be about 6 percent of anthropogenic emissions and

[58] McHenry, J.N., and R.L. Dennis. 1994. Cloud and chemistry pathway characterization of the nonlinear response of sulfur deposition and sulfate air concentrations to changes in SO_2 Emissions in the RADM. In *Atmospheric Chemistry Extended Abstracts.* AMS Conference held January 1994, Nashville, TN. pp. 203–208.

[59] Placet, M., R.E. Battye, and F.C. Fehsenfeld. December 1990. *Emissions Involved in Acidic Deposition Processes.* SOS/T Report 1. In: Acidic Deposition: State of Science and Technology. Volume I. National Acid Precipitation Assessment Program.

[60] Novak, J.H., and T.E. Pierce. 1993. Natural Emissions of Oxidant Precursors. In *Water, Air, and Soil Pollution.* Vol. 67, pp. 57–77.

are not included in the inventory. Natural emissions of nitrogen compounds, which are also poorly characterized, are estimated to be 1 to 2 percent of total nitrogen emissions. The 1985 NAPAP inventory does include nitrogen emissions from soil because these emissions have been studied, although large uncertainties in estimates still exist. Lightning-generated NO_x may be episodically important, but is not understood well enough to be included. Alkaline dust emissions (from sources such as erosion and unpaved roads) are also not included in the inventory. The principal natural source of ammonia, an important nitrogen-containing atmospheric reactant, is animal excrement, from feedlots, farm animals, and wildlife; however, the paucity of data on wildlife densities does not allow this source to be estimated with any degree of reliability. "Natural" emissions of ammonia are included in the inventory, but the estimates have a large degree of uncertainty. Ammonia is considered in RADM simulations because it is an important contributor to nitrogen deposition and affects rainwater pH and the production of secondary sulfate and nitrate aerosols.

Anthropogenic Emissions Sources

Acidic deposition precursor species and reactive atmospheric chemicals are generated by energy production, industrial processes, mobile sources, and waste disposal. Major sources (such as power plants) that emit large quantities of pollutants at specific, well-defined locations are called "point sources." Small emissions sources such as residential boilers and mobile sources are grouped together as "area sources." In general, emissions from point sources are reported to EPA by states, while EPA calculates emissions from area sources. The RADM model includes a species allocation module[61] which accounts for the small amount of primary sulfate (about 1 percent of SO_2 emissions) that is emitted with SO_2. This primary sulfate is negligible in comparison to sulfate formed in the atmosphere. Similarly, the allocation module splits NO_x emissions into a 5:95 ratio of NO_2 to NO. As is the case with biogenic VOC emissions, some VOC species are very reactive in the atmosphere, others are not. The model calculates VOC species or classes by grid cell based on source category.

Major emissions source categories in the United States and their contribution to total emissions of each pollutant in the year 1992 are summarized below for SO_2, NO_x, and VOC.[62]

- SO_2
  - Electric Utility Fuel Combustion (69.7%)
  - Industrial Fuel Combustion (13.6%)
  - Metals Processing (3.8%)
  - Highway Vehicles (3.5%)
  - Other Fuel Combustion (2.6%)
  - All Other Sources (6.8%)
- NO_x
  - Electric Utility Fuel Combustion (32.3%)
  - Highway Vehicles (32.3%)
  - Industrial Fuel Combustion (15.2%)
  - Off-Highway Vehicles (12.3%)
  - Other Fuel Combustion (3.2%)
  - All Other Sources (4.7%)
- VOC
  - Highway Vehicles (26.8%)
  - Solvent Utilization (26.7%)
  - Waste Disposal and Recycling (10.2%)
  - Off-Highway Vehicles (9.4%)
  - Storage and Transport (8%)
  - All Other Sources (18.9%)

Temporal and Spatial Allocation of Emissions Data

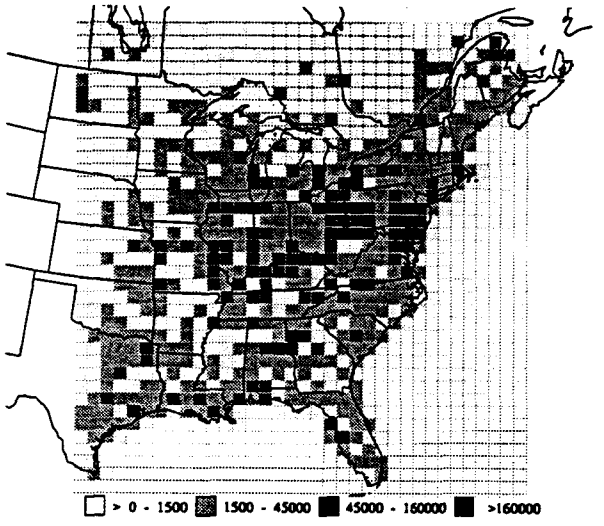
To create modeling inventories the annual inventories must be resolved spatially, temporally, and by chemical species. Allocation of emissions to grid cells for point sources is relatively straightforward. The geographic (latitude-longitude) location of each point source determines its grid cell placement. Since area sources are too small to be included individually in the annual inventory, emissions from these sources are calculated by multiplying an emissions factor by an activity parameter which reflects the operating rate of each source. The activity parameter is determined from surrogates such as population (number of gasoline service stations), housing (residential fuel combustion), and agricultural land area (ammonia fertilizer application). A process was developed by

[61] Walters, R., and M. Saeger. 1990. *The NAPAP Emissions Inventory: Development of Species Allocation Factors.* EPA-600/7-89-010f. U.S. Environmental Protection Agency, Research Triangle Park, NC.

[62] Office of Air Quality Planning and Standards. October 1993. *National Air Pollutant Emissions Trends, 1900–1992.* EPA Report No. 454/R-93-032. U.S. Environmental Protection Agency. Research Triangle Park, NC.

EPA[63] to apportion area source emissions to individual grid cells from county-level data using these surrogate parameters. Exhibit 18 is a density map of SO_2 emissions for the RADM region.

EXHIBIT 18. MAP OF ANNUAL SULFUR EMISSIONS DENSITY IN 1985 (TONS/YEAR)



Day- and hour-specific gridded emissions are created for each of the 30 RADM aggregation cases. Temporal allocation factors were developed for NAPAP[64] that provide day-specific estimates based on tabulation of representative relative diurnal emissions patterns by day of the week and by season for each source. Where emissions strongly respond to temperature and other meteorological conditions, the day-specific meteorology is used in the emissions estimation procedure. Examples include volatile organics that evaporate easily, sources for which ambient conditions affect performance and hence emissions, such as mobile sources, and sources for which temperature affects biological processes, such as biogenic emissions, Plume rise from major industrial and utility sources is also computed hourly, based on the hourly meteorology of each day.

3.2.2 Modeling Source-Receptor Relationships and Source Attribution

Eulerian, or fixed-grid models, are very suitable for representing the full, complex nonlinearity of the photochemistry involved in the oxidation of primary emitted species to acidic substances. The gas- and aqueous-phase oxidation of sulfur is nonlinear; the nonlinearity comes from competition for scarce oxidizers, such as hydrogen peroxide. The most accurate modeling of source-receptor relationships must maintain the overall competition for oxidants represented by the concentrations produced by all the SO_2 emissions, while tracking the particular emissions from the SO_2 sources of interest. In other words, the influence of SO_2 sources cannot be studied individually, but must be considered altogether. This is because, for a nonlinear system, the sum of the deposition from individual point source emissions is not expected to be the same as the total deposition from all point emissions computed simultaneously.

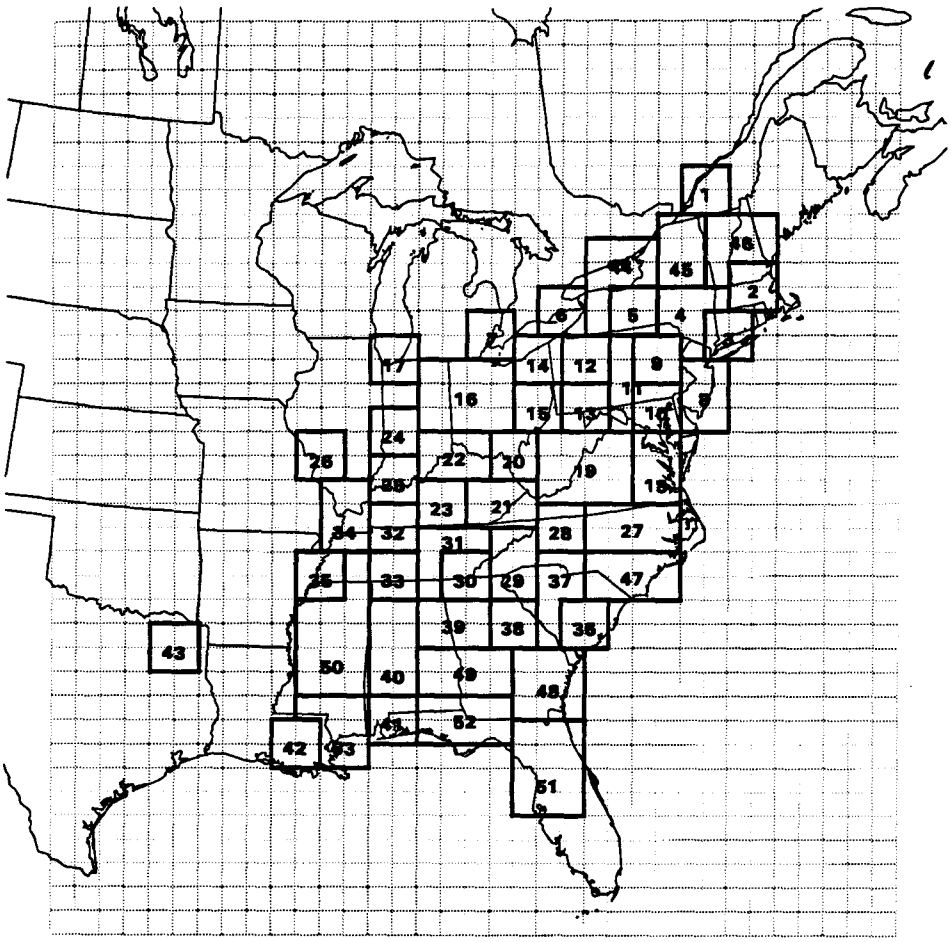
Eulerian models have not historically been used to study source-receptor relationships. The Tagged Species Engineering Model[65] was developed under NAPAP to study such relationships. The Tagged Species Model gives the Eulerian RADM modeling system the capability to identify, for assessment purposes, the concentration and deposition fields attributable to specified SO_2 emissions source regions in the presence of the full concentration fields. The Tagged Model preserves the oxidant competition across space and time. A tagging concept is applied in which additional, identical mass conservation equations are solved for a portion of the sulfur concentration field that originates from specific geographical locations within the full modeling domain. This allows tagged concentration fields and tagged wet and dry deposition to be identified and tracked in the model separate from, yet as portions of, the total sulfur chemical environment that is nonlinear and that produces the complete concentration and deposition fields. Exhibit 19 shows the tagged RADM regions created for the Engineering Model and their geographical

[63] Modica, L., and D.R. Dulleba. April 1990. *The 1985 NAPAP Emissions Inventory: Development of Spatial Allocation Factors.* EPA Report No. 600/7-89-010b. Air and Energy Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC.

[64] Fratt, D., D.F. Mudgett, and R.A. Walters. 1990. *The 1985 NAPAP Emissions Inventory: Development of Temporal Allocation Factors.* EPA Report No. 600/7-89-010d. U.S. Environmental Protection Agency, Research Triangle Park, NC.

[65] McHenry, J.N., F.S. Binkowski, R.L. Dennis, J.S. Chang, and D. Hopkins. 1992. The tagged species engineering model (TSEM). *Atmospheric Environment* 26A(8):1427–1443.

EXHIBIT 19. TAGGED RADM SUBREGIONS[a]



[a] Geographical description of numbered subregions:

1	Montreal Area
2	NH/MA Border
3	NYC/CT
4	Southeast NY
5	Southern Tier NY
6	Niagara Area
7	Detroit Area
8	Central/Southern NJ
9	Eastern PA
10	Southern PA/MD
11	Central PA
12	Northwest PA
13	Southwest PA/Northern WV
14	Cleveland Area
15	OH/WV/PA Border
16	Northewest OH/Eastern IN
17	Chicago Area
18	Eastern VA
19	Western VA/Eastern WV
20	OH/WV/KY Border
21	KY/WV/VA Border
22	Cincinnati Area
23	Central KY
24	Central IL/IN Border
25	Southwest IN/KY Border
26	St. Louis Area
27	Northeast NC
28	Northwest NC
29	Blue Ridge Area
30	NC/TN/GA Border
31	Central TN
32	Central TN/KY Border
33	Central TN/AL Border
34	IL/MO/TN Border
35	Memphis Area
36	Southeast SC
37	Central SC/NC Border
38	Northeast GA
39	Northeast AL/Northwest GA Border
40	Western AL
41	Mobile Area
42	Baton Rouge Area
43	Northeast TX
44	Lake Ontario/NY Shore
45	Adirondacks
46	VT/NH
47	Southeast NC
48	Southeast GA
49	Southern AL/GA Border
50	Northern MS
51	Norther FL Pennisula
52	FL Panhandle
53	Southern MS

description. The use of the Tagged Model in this study represents the first extensive use of a Eulerian model to study source-receptor relationships.

3.2.3 Transport, Chemistry, and Source-Receptor Relationships

The lifetime in the atmosphere of the sulfur dioxide from an emissions source is several days. The main loss mechanisms are the incorporation of SO_2 and sulfate in clouds and the subsequent wet deposition and dry deposition of these species. Thus, SO_2 is transported over many hundreds of kilometers before concentrations from a source are substantially reduced by wet and dry deposition. As a result, the deposition at any one receptor area is coming from a very large number of sources, spread over a large geographic area. Source responsibility cannot be determined, therefore, from monitoring data. Too much is mixed together. Although rough estimates of source-type responsibility can be developed with source apportionment techniques using unique chemical "fingerprints," all assessments of source responsibility or source attribution require the use of an air quality model.

Calculations from the Tagged Species Model illustrate the distances over which SO_2 emissions sources can have an influence. A map of the computed proportion of total annual sulfur deposition contributed by the Ohio/West Virginia/Pennsylvania source subregion (RADM Subregion 15) along the upper Ohio River Valley is shown in Exhibit 20. Exhibit 21 shows the distance covered to deposit increasing fractions of the total deposition in the eastern United States. The subregion's range of influence is more than 1,000 km. Typically, the range of influence of a sub-region extends out to between 500 and 1,200 km. The Tagged Species Model analyses indicate that about two-thirds of the total sulfur deposition from major sources along the Ohio River Valley occurs within 500 to 700 km. For the southern source regions, the distance to deposit about two-thirds of a source's spatially integrated deposition is somewhat less, about 300 to 500 km. The difference in scale of influence is primarily due to meteorology.

A number of meteorological factors influence the existence of dominant transport directions and determine how a group of SO_2 emissions sources influence nearby regions. Key factors are the position of the jet stream, which moves storms across the upper Mid-West; the influence of the Appalachian Mountains on winds and rainfall patterns; the Bermuda highs (stagnation) that move Ohio River Valley emissions in a clockwise direction; and the ocean and Gulf Coast weather that produces lighter winds and more convective conditions, including a typically large proportion of

EXHIBIT 20. PROPORTION OF ANNUAL SULFUR DEPOSITION CONTRIBUTED BY RADM SUBREGION 15 (OH/WV/PA BORDER REGION)

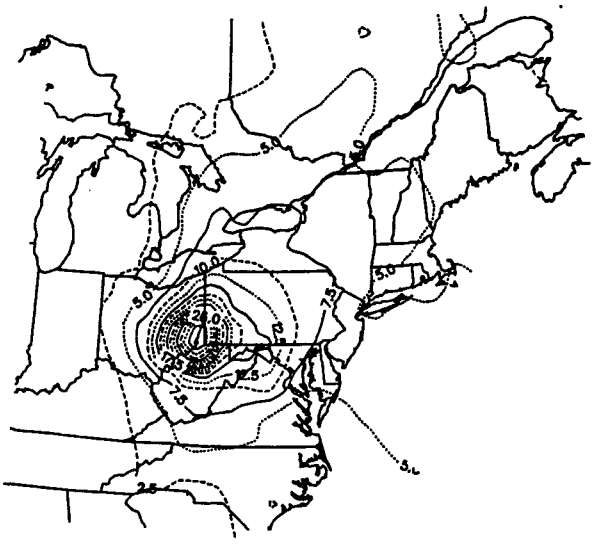
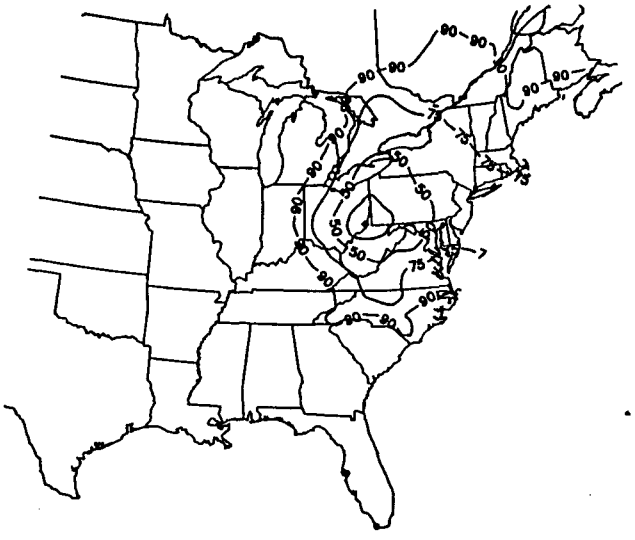


EXHIBIT 21. PERCENTAGE CUMULATIVE RANGE OF INFLUENCE OF RADM SUBREGION 15 (OH/WV/PA BORDER REGION)



convective clouds across the southern states. As a result, source-receptor relationships are skewed to the northeast (Exhibit 22a) starting in northern West Virginia and show a predominantly northerly to easterly quadrant of flow along the lower Ohio River Valley (Exhibit 22b), yet are nearly symmetrical in the Southeast (Exhibit 22c). Thus, the patterns and ranges of source influence can vary. Models, such as those in the RADM system, help to interpret and explain the deposition at receptors of interest.

An alternative approach to determining efficient and cost-effective strategies to achieve deposition targets relies on the use of optimization models.[66] An optimization model for acidic deposition could simultaneously minimize SO_2 removal cost and average exceedance of target deposition rates over the receptor model domain.[67] Such a model could calculate costs and emissions reductions necessary to achieve a regionally averaged target load comparable to the average annual deposition level calculated by RADM. This model was investigated for this report but not used because of the computational difficulty in combining the nonlinear RADM transfer coefficients into a linear programming optimization model. Although an optimization model could have been employed using linear transfer coefficients, at the time this report was being developed, no linear transfer coefficients that approximated the RADM transfer coefficients were available. Optimization models are, however, used extensively when important

EXHIBIT 22A. SOURCE-RECEPTOR RELATIONSHIPS IN THE NORTHEAST: CUMULATIVE PERCENT SULFUR DEPOSITION

EXHIBIT 22B. SOURCE-RECEPTOR RELATIONSHIPS IN THE LOWER OHIO VALLEY: CUMULATIVE PERCENT SULFUR DEPOSITION

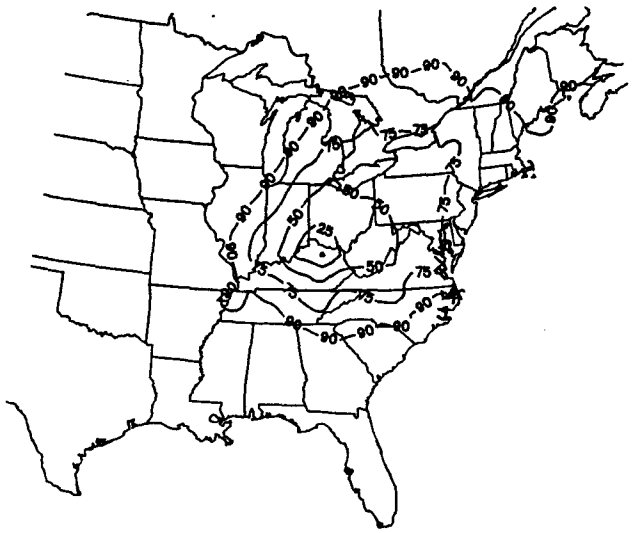
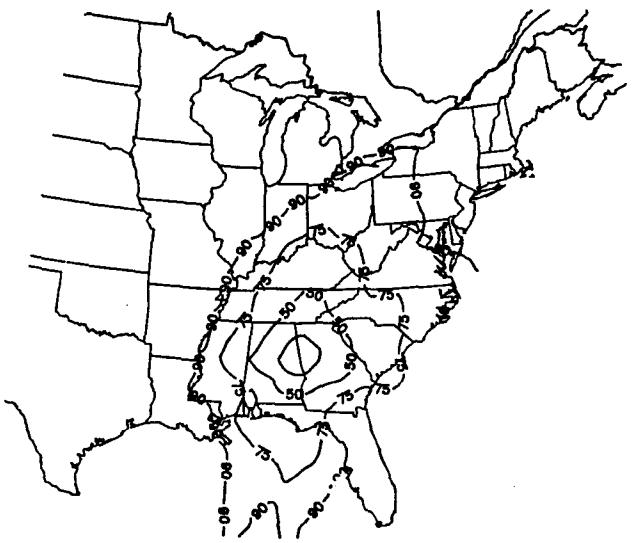


EXHIBIT 22C. SOURCE-RECEPTOR RELATIONSHIPS IN THE SOUTHEAST: CUMULATIVE PERCENT SULFUR DEPOSITION



[66] Streets, D.G., D.A. Hanson, and L.D. Carter. 1984. Targeted strategies for control of acidic deposition. *Journal of the Air Pollution Control Association* 34(12):1187–1197.

[67] Ellis, J.H. 1988. Multiobjective mathematical programming models for acid rain control. *European Journal of Operational Research* 35(3):365–377.

critical or target load decisions have already been made (e.g., in European countries). Development of linear transfer coefficients consistent with RADM are beyond the scope of this study.

3.2.4 Confidence in Results

The United States and Canada have been cooperating in a bi-national Eulerian Model Evaluation Field Study (EMEFS) and model evaluation since 1985.[53] U.S. data collection for EMEFS was conducted under the auspices of NAPAP. Phase 1 of the evaluation of the two advanced acidic deposition models ADOM (Acid Deposition and Oxidants Model) and RADM (Regional Acid Deposition Model) has been completed and described.[68] Phase 1 was primarily based on 1988 EMEFS data. Improvements to RADM resulted and uncertainty analyses regarding the scientific assumptions in the model were prepared that went beyond the earlier NAPAP results (outlined in reference 3). Phase 2, the final phase of the evaluation, has been completed and is based on the 1990 EMEFS data as well as data of high diagnostic value from the 1988 period. A cooperative effort in the evaluation of the advanced models will continue under the U.S.-Canada Air Quality Agreement.

At the end of Phase 1 and Phase 2, the evaluation results were subjected to extensive external peer review. The review focused on how well the evaluation had followed the preset protocol, the resulting credibility of the models, and the appropriateness of model applications. The review panel members determined they would have confidence in the ability of the models to represent (1) total sulfur loading of the atmosphere, suggesting that the emissions inventory and average lifetimes of sulfur species are roughly correct; (2) annual sulfur deposition, although there is some seasonal bias, with deposition being underestimated in summer and overestimated in winter; and (3) total nitrogen loading of the atmosphere, suggesting that the nitrogen budget and average lifetime of nitrogen species is roughly correct.

From the Phase 1 review, the external review panel felt that the models could be used for estimating annual deposition of sulfur and nitrogen. The reviewers concluded that, while both models were adequate for the study of large-scale and long-distance source-receptor relationships, the models are so complex that their application to the problem of source-receptor relationships might be more limited. A valuable application would be for the complex models to serve as a check on the accuracy of the simpler, but much faster, Lagrangian methods or on the source-receptor matrices produced by the Lagrangian methods. Regarding nonlinearities in the sulfur deposition, the reviewers agreed that they may be of the order of 10 percent to 15 percent. However, they noted there is no observational means of fully testing the validity of the model estimates of the relatively modest nonlinear effects. The panel concluded that a great deal had been accomplished and significant improvements had been made in the models during the evaluation process. The protocol and evaluation have been essential in winning scientific support for the models, and the models have shown evidence of converging towards operational use. This process, however, is more advanced for sulfur than for applications involving nitrogen.[69]

As part of the model evaluation process, bounding studies were performed to assess the risk that the predicted changes in air concentrations and deposition would be sensitive to uncertainties in the scientific descriptions in RADM. The bounded range of RADM predictions is roughly 10 percent around the best estimate of deposition change. There is greater confidence in the upper bound, but less in the lower bound because it is affected by our lack of complete understanding of the nonlinear processing affecting sulfur deposition. The narrow range would suggest that there is little risk that the model will misguide users regarding the predicted change in sulfur deposition, despite shortcomings uncovered in the model evaluation. This appraisal of the bounding results may change if significant new insight or knowledge develops in the future.

3.3 SOURCE ATTRIBUTION

3.3.1 Changes from 1985 to 2010

Fifty-three tagged regions were identified in Exhibit 19 for which the major point source SO_2 emissions (utility and major industry) have been

[68] Pacific Northwest Laboratories. 1991. *The Eulerian Model Evaluation Field Study.* Interim report PNL-7914. Prepared for the U.S. Environmental Protection Agency, Research Triangle Park, NC. IAG DW89933040-01, 81 pp.

[69] U.S. Environmental Protection Agency. 1994. *Progress Report for the U.S.-Canada Air Quality Agreement.*

explicitly tracked, using the RADM Tagged Species Engineering Model. These regions account for 84 percent of the major point source emissions in the United States during 1985 and 76 percent in 2010. Exhibit 23 shows the percentage contributions of the 53 tagged regions to U.S. major point SO_2 emissions in the RADM domain, to total U.S. SO_2 emissions in the RADM domain, and to all North American SO_2 emissions in the Northeast, respectively. Thus, although the 53 tagged regions accounted for three-quarters of the 1985 total SO_2 emissions, by 2010, after implementation of the 1990 CAAA, they will account for about 60 percent of the U.S. emissions of SO_2 from all sources.

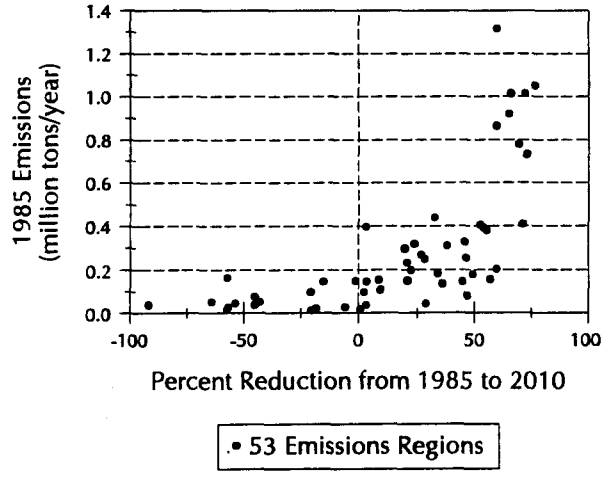
EXHIBIT 23. PERCENT CONTRIBUTION TO SULFUR EMISSIONS OF 53 TAGGED RADM REGIONS

	RADM SO_2 Emissions Data		
Year	53 Regions: Percent of U.S. Major Point Sources	53 Regions: Percent of Total U.S. Sources	53 Regions: Percent of Total North American Sources
1985	83.6%	74.8%	66.6%
2010	75.7%	63.6%	54.3%
Year	53-Region Total Tagged Emissions	Total Major U.S. Point Emissions	Total Emissions from All U.S. Sources
1985	15,420,000 tons	18,452,000 tons	20,323,000 tons
2010	9,265,000 tons	12,245,000 tons	14,557,000 tons

The listing of emissions by tagged-source region shows that emissions per unit area are being leveled out by Title IV. This is shown in Exhibits 24 and 25. Exhibit 24 quantifies this by comparing the percent reduction between 1985 and 2010 as a function of the 1985 SO_2 emissions contributed by each of the 53 regions. The top 8 emitting regions in 1985 will have the largest percent reductions by 2010, around 50 to 60 percent. A major fraction of the regions, those with emissions between 100,000 and 450,000 tons/year, have their SO_2 emissions reduced between 10 and 50 percent, forming a second tier of reductions. Emissions from most of the smallest emitting regions (≤100,000 tons/year) actually increase (negative percent change) between 1985 and 2010, thereby increasing in importance in analyses regarding additional emissions reductions beyond the CAAA. The result is a modest leveling out of responsibility for the emissions, as shown in Exhibit 25.

Exhibit 26 shows the percentage contributions of the top 10 emitting regions of 1985 and 2010 to deposition in the three sensitive regions. Eight of the top 10 in 1985 are still in the top 10 in 2010. But, the top 10 emitters are responsible for a smaller fraction of the deposition in the sensitive regions in 2010 than they were in 1985. The fraction of the total deposition attributable to the top 10 emitters goes down by 32 percent, 24 percent, and 52 percent for the Adirondacks, the mid-Appalachians, and the Southern Blue Ridge, respectively. The change is largest for the Southern Blue Ridge, resulting in the top 10 emitting regions being responsible for only 16 percent of the sulfur deposition in 2010.

EXHIBIT 24. PERCENT REDUCTION IN TAGGED REGIONS FROM 1985 TO 2010 AS A FUNCTION OF RELATIVE CONTRIBUTION OF EACH REGION TO ALL TAGGED EMISSIONS



3.3.2 Regional Emissions Distribution in 2010

With greater emissions reductions coming from the heavier-polluting regions, the relative importance of

EXHIBIT 25. PERCENTAGE OF TAGGED EMISSIONS BY TAGGED REGIONS FOR 1985 AND 2010

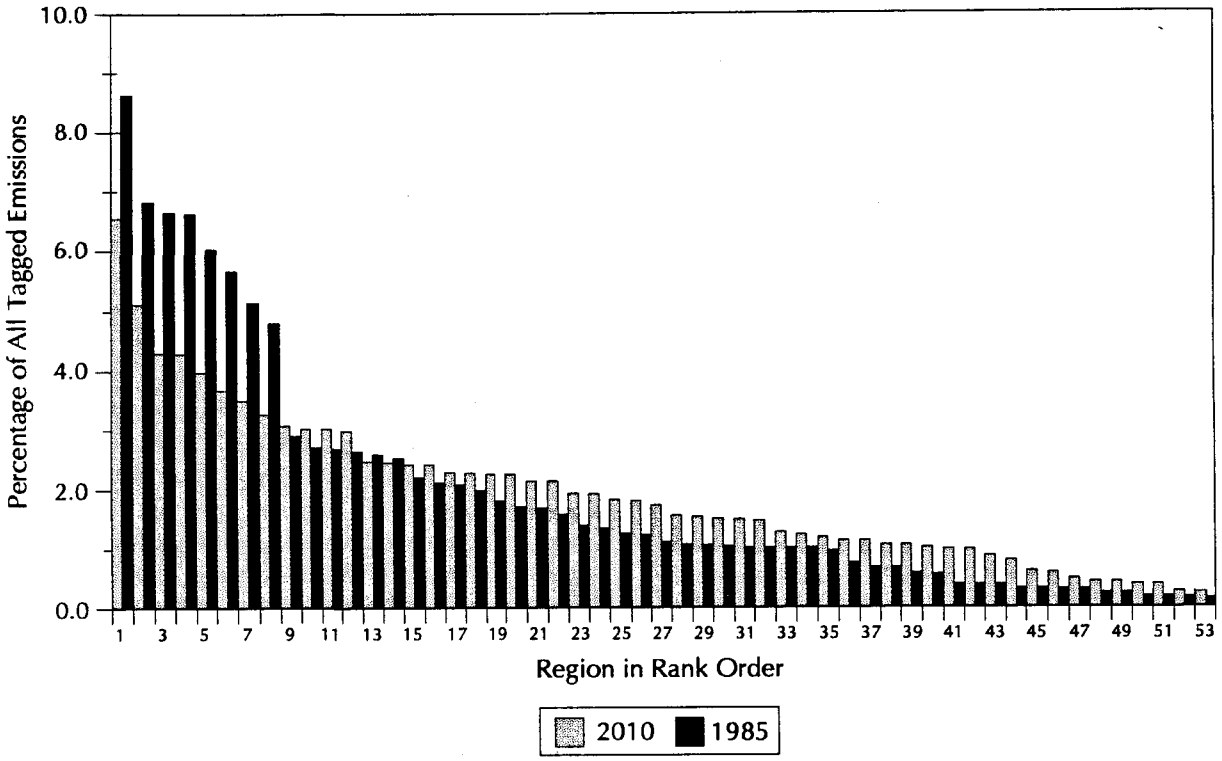


EXHIBIT 26. CONTRIBUTION OF TOP-10 SO_2 EMITTING REGIONS TO SULFUR DEPOSITION IN SENSITIVE REGIONS

Year	Top-10 SO_2 Emitting Regions[a]	Adirondacks	Mid-Appalachians	Southern Blue Ridge
1985	15,26,39,13,22,20,25,32,7,24	30.2%	49.4%	30.8%
2010	15,13,22,20,51,26,25,39,7,17	20.6%	37.3%	16.1%

[a] See Exhibit 19 for geographical descriptions of RADM subregions.

long-range transport is expected to decrease in 2010 compared to 1985. The character of the source contributions in 2010 is important to any analyses of further emissions control to reduce deposition. Two aspects stand out: first, in the mid-Appalachians and Southern Blue Ridge significant contributions to sulfur deposition come from sources near the sensitive aquatic regions; second, the local versus long-range character of the sources of deposition changes when moving south from the Adirondacks to the mid-Appalachians and the Southern Blue Ridge. The importance of the top emitting regions decreases as one moves north or south away from the mid-Appalachians. This results from a combination of meteorology (transport directions), proximity to large emissions sources, and the pattern of emissions in 2010.

Exhibit 27 shows that, as one moves from the Adirondacks to the mid-Appalachians and Southern Blue Ridge, emissions sources near sensitive areas are responsible for a greater percentage of deposition relative to the contributions from the top 10 emissions regions. This can be seen by noting the contribution to deposition from source regions as one moves from row A to row D. For the Adirondacks, the 10 regions contributing the most to deposition are responsible for about 3.5 times more deposition than do nearby sources (row D versus

EXHIBIT 27. COMPARISON OF PROXIMATE AND MAJOR EMITTING REGIONS TO SULFUR DEPOSITION IN SENSITIVE AREAS IN 2010

Geographic Source of Deposition	Adirondacks	Mid-Appalachians	Southern Blue Ridge
A. Sources local to sensitive region	3.7%	24.0%	12.0%
B. Sources local and contiguous to sensitive regions	7.8%	28.0%	26.0%
C. Sources from top-10 deposition contributing regions (utilities only)	20.0%	37.0%	34.0%
D. Sources from top-10 deposition contributing regions (utilities plus industry)	28.0%	46.0%	41.0%

row B). In the mid-Appalachians and the Southern Blue Ridge the top emitting regions contribute only 60 percent more deposition than do nearby regions. In these two receptor regions several of the regions contributing large amounts of deposition are either local or contiguous to the receptor regions. The importance of the contribution from the top emitting regions (primarily located along the Ohio River Valley) to the deposition in the sensitive regions, and hence, the importance of long-range transport, decreases as one moves from north to south. This source attribution insight is used in Section 3.6 to analyze a regionally targeted emissions reduction approach to achieving deposition reductions of sulfur.

3.4 EMISSIONS REDUCTIONS SCENARIOS

This section describes emissions scenarios created to evaluate the impact of Title IV on sensitive regions and the environmental impact of additional emissions reductions beyond those mandated by Title IV. This analysis concentrates on emissions of SO_2 and deposition of sulfur because Title IV focuses on SO_2 emissions and because emissions inventories and source-receptor relationships are better characterized for sulfur than for nitrogen, the other key pollutant contributing to acidic deposition. A scoping analysis of nitrogen deposition is included. The scenarios are used in this chapter to compare deposition levels in sensitive regions. Cost and economic impacts of sulfur reductions scenarios are presented in Chapter 5, Implementation.

Two sets of scenarios for SO_2 emissions in 2010 (the year Title IV will be fully implemented) were developed. The first was created to evaluate the environmental impacts (i.e., changes in deposition) resulting from the trading of SO_2 emissions allowances. The second represents additional SO_2 emissions reductions beyond those mandated by Title IV. The environmental impacts of these scenarios are compared to the pre-CAAA case (1980). One scenario was developed to compare NO_x reductions with 1990 baseline emissions levels. Base years for SO_2 and NO_x emissions were selected based on the availability of data at the time of this analysis.

Emissions for each scenario were projected from existing EPA emissions inventories. The National Allowance Data Base (NADB) was used as the basis for electric utility SO_2 emissions estimates and projections. EPA developed the NADB to allocate and track SO_2 allowances issued under Title IV. The NADB was prepared by updating the utility emissions data base (the 1985 National Unit Reference File or NURF) included in the 1985 NAPAP Emissions Inventory. The basis for non-utility SO_2 emissions estimates is the 1985 NAPAP Emissions Inventory for Canadian and U.S. emissions. The basis for NO_x emissions estimates for utilities and industrial sources is EPA's 1990 Interim Emissions Inventory.[70] As with the NADB, the 1990 Interim Inventory was developed by updating the 1985 NAPAP Emissions Inventory. The 1985 inventory was updated for 1990 using industry growth rates, EPA's Mobile 4.1 model for mobile sources, and by adding electric utility units that became operational between 1985 and 1990. The 1980 SO_2 emissions inventory used to calculate 1980 sulfur

[70] U.S. Environmental Protection Agency. June 1992. *Regional Oxidant Modeling—Emissions Inventory Development and Emission Control Scenarios.*

U.S. Environmental Protection Agency, May 1989. *Regional Ozone Modeling for Northeast Transport—Development of Base Year Anthropogenic Emissions Inventory.*

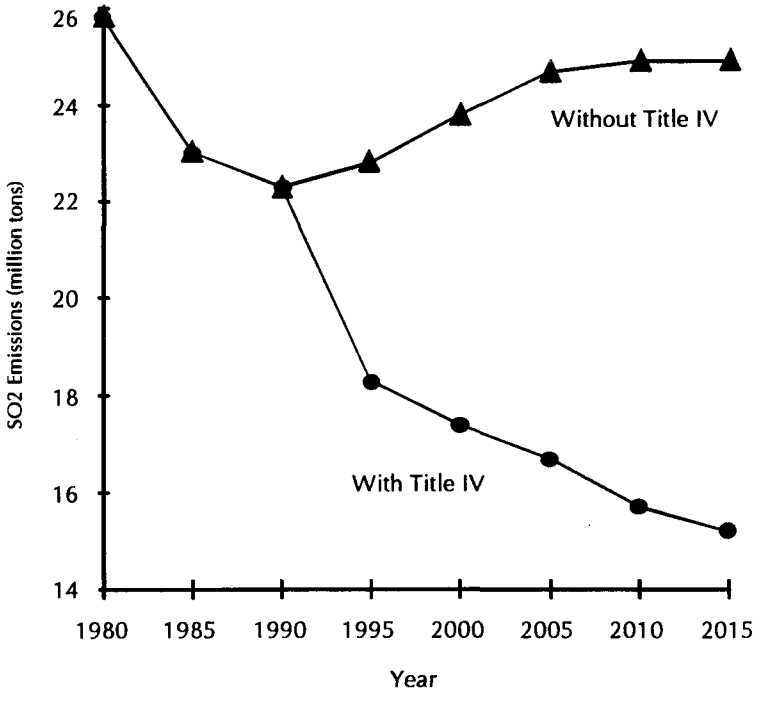
deposition was developed for EPA's retrospective cost/benefit analysis of the CAA conducted pursuant to section 812 of the 1990 Amendments. This inventory was constructed by backcasting emissions from the 1985 NAPAP emissions inventory.

The base year for evaluating the environmental impacts of the CAAA and the benefits of additional SO_2 emissions reductions beyond the CAAA is 2010. Utility emissions for 2010 were forecasted in EPA's 1993 Base Case Analysis,[71] which was developed to support rulemaking under Title IV. Existing and planned electric utility boilers identified in NADB Version 3.11 plus generic plants required to meet growth in electricity demand were used as a basis for the SO_2 forecasts. For EPA's 1993 Base Case Analysis, electric utility SO_2 emissions were projected from the NADB inventory using ICF's Coal and Electric Utilities Model (CEUM). EPA's analysis assumed full implementation of allowance trading (i.e., electric utilities would engage in allowance trading in order to minimize the overall cost of reducing SO_2 emissions by 10 million tons below 1980 levels).

Projections of 2010 non-utility SO_2 emissions from the 1990 Interim Inventory were based on a straightforward approach developed by EPA.[72] First, emissions from the 1990 Interim Inventory were grown according to the Bureau of Economic Affairs (BEA) industrial earnings growth factor (i.e., by 2-digit SIC code and state). Next, the grown emissions were adjusted to reflect the retirement of existing sources, new emissions (assumed to be subject to New Source Performance Standards [NSPS]) to replace those lost due to retirement, and the application of additional controls required by the CAAA. In total non-utility SO_2 emissions did not change significantly between 1990 and 2010.

Projected nationwide total annual emissions of SO_2 with and without implementation of Title IV are shown in Exhibit 28. The projections are based on CEUM predictions of utility emissions with and without Title IV and predictions of non-utility emissions calculated as described in the previous paragraph. Annual SO_2 emissions decreased by about 14 percent between 1980 and 1990. Without Title IV annual emissions would slowly begin to increase after 1990 and almost reach 1980 levels by 2010. Under Title IV SO_2 emissions will decrease dramatically after 1990, achieving a 10 million ton reduction from 1980 levels by 2010.

EXHIBIT 28. ESTIMATED U.S. SO_2 EMISSIONS WITH AND WITHOUT TITLE IV FROM 1980 TO 2015



Under Title IV utilities are allowed to defer the use of allowances to future years, i.e. bank allowances. The Nitrogen Bounding Study, discussed in Chapter 2, calculates the aquatic impact of deposition in the year 2040 based on deposition values between 2010 and 2040. EPA has projected SO_2 emissions only through 2010 because the assump-

[71] ICF Resources, Inc. February 1994. *Economic Analysis of the Title IV Requirements of the 1990 Clean Air Act Amendments.* Prepared for U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division.

[72] U.S. Environmental Protection Agency, May 1993. *Regional Interim Emissions Inventories (1987–1991).* Volume I: Development of Methodologies.

tions underlying the CEUM are assumed to be valid only through that year. Exhibit 29 shows national utility SO_2 emissions predicted by CEUM for the years 1990–2010. The model predicts that several million allowances will be banked in the early years of the allowance trading program (resulting in early emissions reductions) for use between the years 2000 and 2010, with almost 1 million banked allowances used in 2010. Thus, SO_2 emissions in the year 2010 will be almost 1 million tons higher than in subsequent years. A no-banking (post 2010 full implementation) scenario was created for purposes of this analysis to represent typical emissions for the years 2010 through 2040, and thus to better reflect deposition modeled in the Nitrogen Bounding Study.

The emissions inventories for the alternative scenarios for SO_2 in 2010 were developed for the RADM domain (eastern United States, see Exhibit 17) as follows and are summarized in Exhibit 30:

- 2010 SCENARIO: This scenario represents utility SO_2 emissions in 2010 forecast by the CEUM in the 1993 Base Case Analysis described above. Utility emissions in this scenario total 9.5 million tons in 2010. The following two scenarios were calculated from this inventory.

- POST-2010 FULL IMPLEMENTATION SCENARIO: Utility SO_2 emissions from the 2010 scenario were reduced to allowance levels in 2010 (the 8.95 million ton cap mandated by Title IV) by removing emissions banked from previous years (see Exhibit 29). This scenario was developed to represent full implementation of Title IV after 2010. Utility emissions in years beyond 2010 should remain near this level. Non-utility emissions were unchanged from the 2010 scenario.

- 2010 NO-TRADING SCENARIO: Existing units operating in 2010 were forecast to emit SO_2 at their allowance levels. Allowances issued to units retiring before 2010 (0.14 million) were assigned to new units. This scenario also assumes (based on the EPA 2010 Base Case Forecast Without Title IV) that oil and gas-fired units, which were allocated allowances, would have emissions that are 0.3 million tons less than their allowance allocations. Of the total of 0.44 million tons of allowances, 0.19 million tons were assumed to be allocated to new units, leaving 0.25 million tons unused. Thus total nationwide utility SO_2 emissions in this scenario are 8.95 million tons less the 0.25 unused allowances or 8.7 million tons. Non-utility emissions were unchanged from the 2010 scenario.

- ADDITIONAL UTILITY SO_2 REDUCTION SCENARIO (UTILITY SO_2 EMISSIONS REDUCED BY 50 PERCENT FROM THE POST-2010 FULL IMPLEMENTATION SCENARIO): Total electric utility SO_2 emissions were reduced by 50 percent from the Post 2010 Full Implementation Scenario. To allocate this reduction units included in the baseline scenario able to achieve significant reductions in SO_2 emissions (i.e., those with emissions rates forecast to be greater than 0.8 pounds of SO_2 per million British thermal unit [lbs/MMBtu]) were identified. From this group, the set of boilers able to most cost-effectively reduce SO_2 were selected based on Cadmus' Generic Retrofit Scrubbing Cost Model. The 50 percent utility reduction was then pro-rated by state. Baseline emissions for the set of boilers with SO_2 emissions rates greater than 0.8 lbs/MMBtu were reduced in proportion to the pro-rated state reduction.

- ADDITIONAL INDUSTRIAL SO_2 REDUCTION SCENARIO (INDUSTRIAL SO_2 EMISSIONS REDUCED BY 50 PERCENT FROM THE POST-2010 FULL IMPLEMENTATION SCENARIO): SO_2 emissions in the RADM domain for the 2010 projection described above were estimated to total about 4 million tons. A 2 million ton reduction was achieved from industrial boilers and major process industries (categories projected to emit more than 10,000 tons in 2010). As described in more detail in Chapter 5, cost-effectiveness measures (annual cost per ton of SO_2 removed) were calculated for each sector to allocate the 2 million ton reduction. Based on this analysis, industrial boilers accounted for 63 percent and industrial sources 37 percent of the emissions removed.

- ADDITIONAL UTILITY AND INDUSTRIAL SO_2 REDUCTION SCENARIO (UTILITY AND INDUSTRIAL SO_2 EMISSIONS REDUCED BY 50 PERCENT FROM THE POST-2010 FULL IMPLE-

EXHIBIT 29. PREDICTED SO_2 UTILITY EMISSIONS FROM 1990 TO 2010

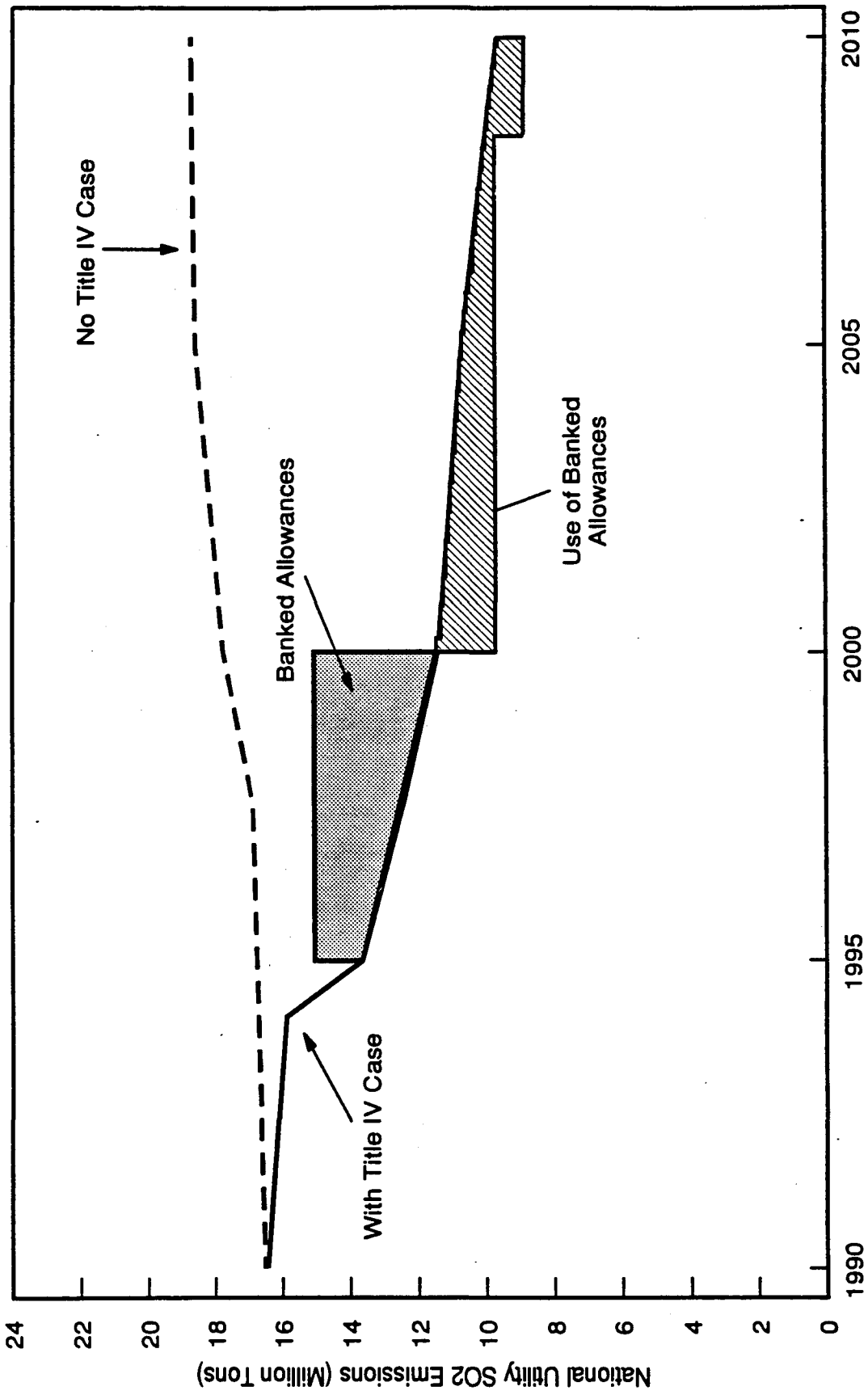


EXHIBIT 30. SO_2 EMISSIONS IN THE U.S. RADM DOMAIN (EASTERN UNITED STATES)

Scenario	SO_2 Emissions (million tons)
1980	24.8
1985 NAPAP	20.3
2010	14.6
Post-2010 full implementation scenario	14.0
No Trading	13.7
Additional utility SO_2 reduction	9.7
Additional utility and industrial SO_2 reduction	7.8

MENTATION SCENARIO): Combination of the two previous scenarios. As shown in Section 3.2.1, utility and industrial sources account for 87 percent of total nationwide SO_2 emissions. Thus, a 50 percent reduction in utility and industrial SO_2 emissions represents a 43.5 percent reduction in total SO_2 emissions.

- ADDITIONAL UTILITY AND INDUSTRIAL NO_x REDUCTION SCENARIO (UTILITY AND INDUSTRIAL NO_x EMISSIONS REDUCED BY 50 PERCENT FROM THE 1990 INTERIM EMISSIONS INVENTORY): 1990 emissions from each unit were reduced by half. As shown in Section 3.2.1, utility and industrial sources account for 47.5 percent of total nationwide NO_x emissions. Thus, a 50 percent reduction in utility and industrial NO_x emissions represents only a 24 percent reduction in total NO_x emissions.

3.5 DEPOSITION REDUCTIONS UNDER VARIOUS NATIONAL EMISSIONS REDUCTIONS SCENARIOS

Total sulfur or nitrogen deposition to each 80 by 80 km grid cell in the RADM region was calculated for each scenario in Exhibit 30. Sulfur deposition in the units of kilograms of sulfur per hectare per year (kg-S/ha/yr) is the sum of wet and dry sulfate; nitrogen deposition (in units of kg-N/ha/yr) consists of wet and dry nitrate and wet and dry ammonia. This section is divided into three parts: sulfur deposition reductions under Title IV and an analysis of trading; additional sulfur deposition emissions beyond Title IV; and nitrogen deposition reductions.

3.5.1 Impact of SO_2 Allowance Trading on Sulfur Deposition

Exhibit 31 is a map of the spatial distribution of total sulfur deposition in the RADM region for the pre-CAAA year of 1980. The highest sulfur deposition levels, more than 20 kg-S/ha/yr, were in the industrial area encompassing parts of West Virginia, Pennsylvania, Ohio, Kentucky, and Indiana and in the mid-Appalachians. Deposition levels were about 20 percent lower in the Southern Blue Ridge and Pocono Mountains and about 40 percent lower in the Adirondacks. Thus, the highest deposition levels are in or just downwind of the highest emitting areas.

EXHIBIT 31. ANNUAL AVERAGE RADM TOTAL SULFUR DEPOSITION (KG-S/HA): 1980

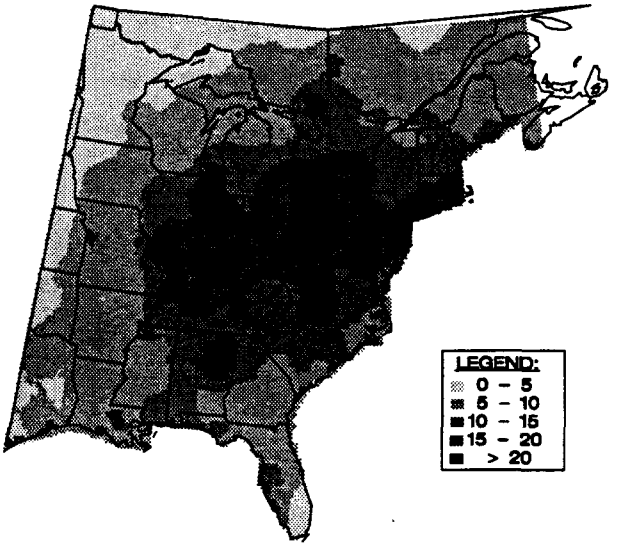


Exhibit 32 is the same map projected for the post 2010 full implementation scenario. The spatial distribution of emissions in 2010 is similar to that of 1980. In 2010 deposition levels in the Southern Blue Ridge are projected to be about 15 percent lower and those in the Adirondacks about 40 percent lower than in the industrial mid-West and mid-Appalachians. Similar spatial distributions are also found for the 2010 and 2010 no-trading scenarios. Exhibit 33 is a map of percentage reductions in sulfur deposition from 1980 to the post 2010 full implementation scenario. This map again demonstrates that the largest deposition reductions

EXHIBIT 32. ANNUAL AVERAGE RADM-PREDICTED TOTAL SULFUR DEPOSITION (KG-S/HA): POST-2010 FULL CAAA IMPLEMENTATION

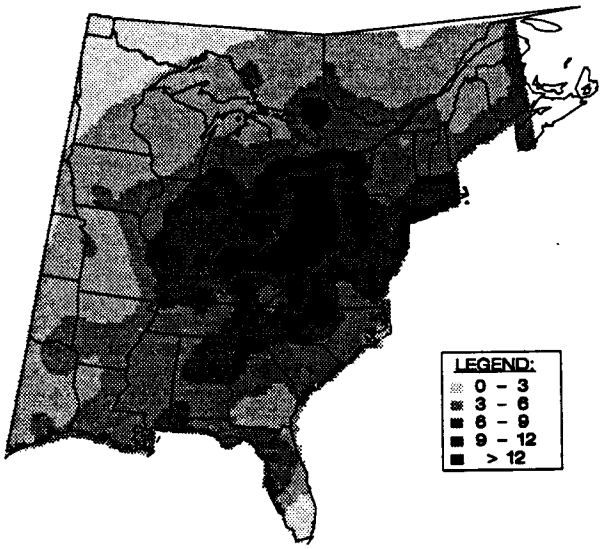
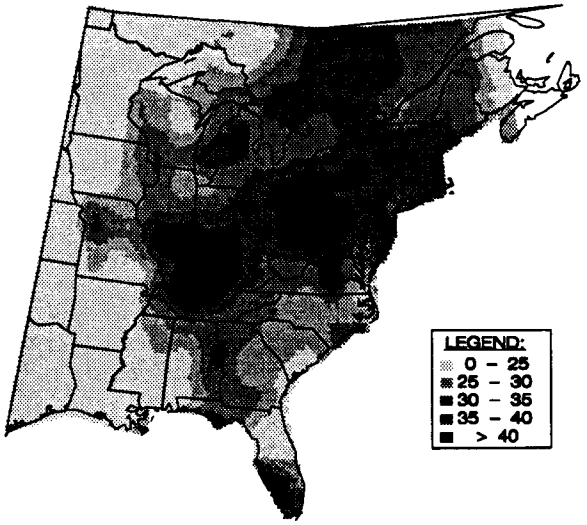


EXHIBIT 33. PERCENTAGE REDUCTIONS IN SULFUR DEPOSITION FROM CAAA IMPLEMENTATION



tions, over 40 percent, are in the highest emitting regions.

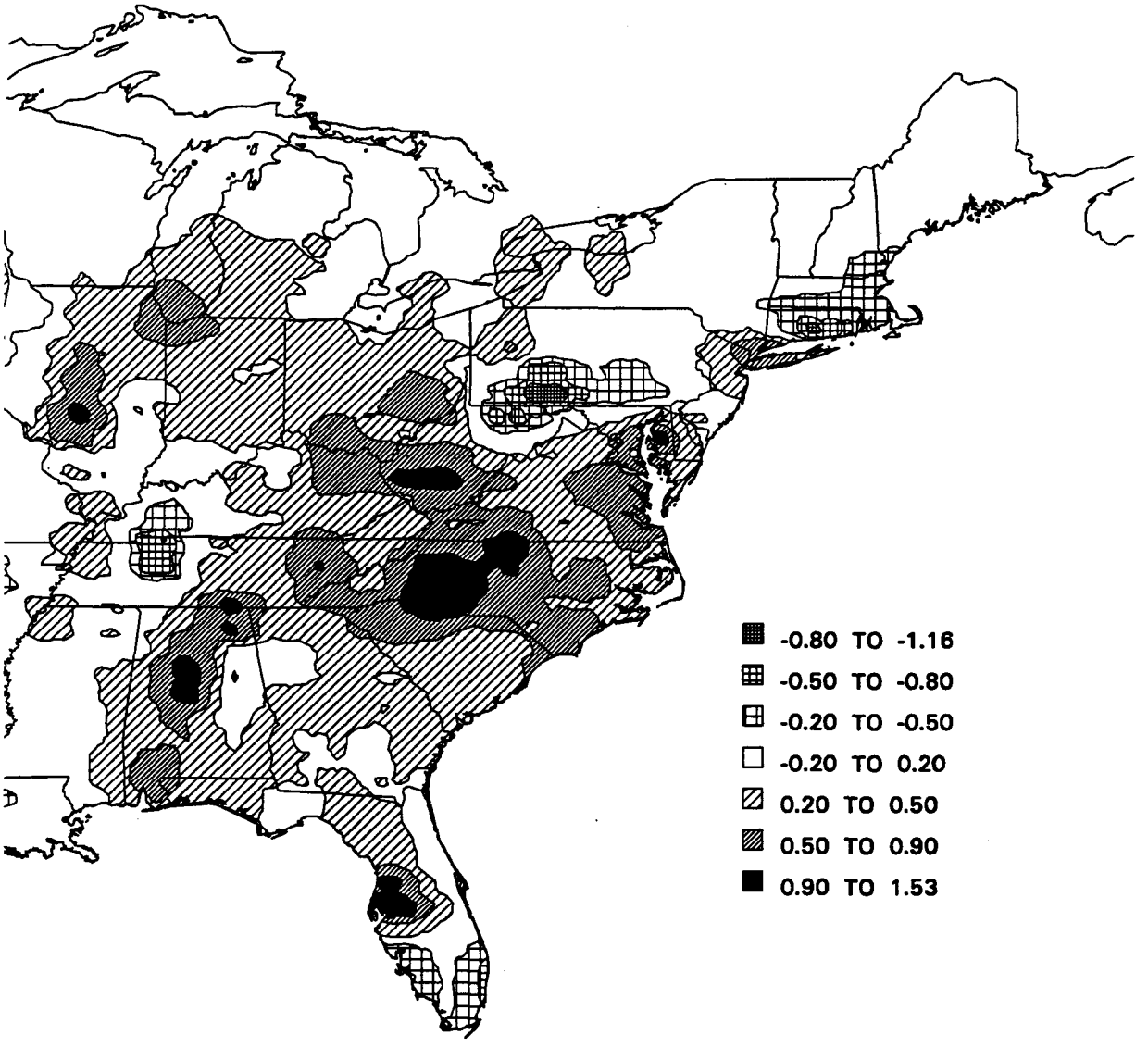
Exhibit 34 compares annual average sulfur deposition for the 2010 (with trading), no-trading, and post 2010 full implementation scenarios for the three sensitive regions analyzed for this report. The 1980 and 1985 deposition values are included for reference. The most consistent comparison to assess the impact of allowance trading is between the post 2010 full implementation and no-trading scenarios. For the post 2010 full implementation scenario sulfur deposition in the Adirondacks and mid-Appalachians is reduced about 40 percent from 1980 and reduced about 30 percent in the Southern Blue Ridge. The deposition values and percent reductions are essentially the same for the no-trading case in the Adirondacks and the mid-Appalachians. The lower total RADM-wide SO_2 emissions for the no-trading case shown in Exhibit 30 most likely accounts for the 0.1 kg-S/ha difference in deposition in the Adirondacks. In the Southern Blue Ridge the deposition (9.2 kg-S/ha) is lower and the percent reduction (34 percent) is higher for the no-trading case.

A more detailed spatial view of the differences in sulfur deposition between the post 2010 full implementation and no-trading scenarios for 2010 is given in the map in Exhibit 35. The areas shaded diagonally and in solid black depict areas where projected regional deposition would be higher with trading. The areas shaded with a plaid pattern are those where projected deposition would be lower with trading. The largest increases associated with trading, somewhat more than 1.2 kg-S/ha or about 10 percent of total deposition, are near the Southern Blue Ridge and in northern Alabama. Most of the increases are 0.2–0.8 kg-S/ha, less than 10 percent of the total sulfur deposition. Note that the allowance trading program cannot result in exceedance of a National Ambient Air Quality Standard (NAAQS), and thereby will not create or intensify local air quality or public health problems, because sources must always comply with the requirements of the NAAQS as well as the

EXHIBIT 34. IMPACT OF TRADING ON SULFUR DEPOSITION IN SENSITIVE REGIONS

Emissions Scenario	Annual Average Deposition Level (kg-S/ha)		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
1980	11.0	19.0	14.0
1985 NAPAP	9.8	17.0	13.0
2010 (with trading)	7.1	12.0	9.9
Post-2010 full implementation	6.9	11.0	9.7
2010 (without trading)	6.8	11.0	9.2

EXHIBIT 35. DIFFERENCE IN ANNUAL AVERAGE RADM TOTAL SULFUR DEPOSITION (KG-S/HA) IN 2010 BETWEEN POST 2010 FULL IMPLEMENTATION AND NO TRADING SCENARIOS



Prevention of Significant Deterioration Program (e.g., in National Parks and Wilderness Areas). There are a few small regions where deposition is projected to decrease due to trading. These are in southern New England, southern Florida, and northwestern Tennessee. Exhibit 35 shows that the lack of a difference in deposition in the mid-Appalachians between post 2010 full implementation and no-trading scenarios listed in Exhibit 34 is due to increases in one area being offset by decreases in another. Nonetheless, the modeling estimates of the differences in sulfur deposition between the post 2010 full implementation and no-trading scenarios indicate that they are expected to be less than 10 percent, and in many cases much less in the sensitive aquatic regions. It is also apparent from Exhibit 35 that trading has virtually no impact on sulfur deposition in Canada.

3.5.2 Effect of Additional SO_2 Emissions Reductions on Sulfur Deposition

This section presents deposition values for the additional SO_2 reduction scenarios described above and compares each to the post 2010 full implementation scenario. The additional reductions scenarios were chosen to demonstrate the

magnitude of further emissions reductions and the spatial distributions associated with each. Exhibits 36 and 37 are sulfur deposition maps for 50 percent additional utility SO_2 reductions, and 50 percent utility plus 50 percent industrial SO_2 reduction scenarios. Exhibits 38 and 39 are maps of percentage reductions in sulfur emissions relative to the post 2010 full implementation case for each scenario. Exhibit 40 summarizes the annual average deposition to the three sensitive regions for each scenario, and Exhibit 41 lists the percentage decrease in sulfur deposition to each region relative to 1980.

By comparing the sulfur deposition maps for the additional reductions scenarios (Exhibits 36 and 37) to the deposition map for the post 2010 full implementation case (Exhibit 32), it is apparent that the general spatial distribution of sulfur deposition remains similar with the highest deposition values falling in the industrial areas of the mid-West, the regions with the highest emissions. Exhibits 38 and 39 show that the percentage reductions increase as one moves south, with the largest percentage reductions occurring from the lower Ohio Valley through Florida, with significant reductions in central New York State. The reduction in industrial emissions has the greatest impact in the Southern Blue Ridge and South Atlantic regions.

3.5.3 Decrease in Total Nitrogen Deposition from Decreases in NO_x Emissions

Nitrogen deposition is primarily the sum of wet and dry deposition of nitrate and ammonia. (There is also a small contribution from dry NO_2.) As noted in Section 3.2.1, emissions estimates for ammonia are highly uncertain both in terms of magnitude and source. Therefore, RADM replaces predicted ammonia with observed ammonia deposition. In deposition modeling the contribution of ammonia to nitrogen deposition is treated as background along with nitrogen deposition from oxidized species from natural sources and agricultural emissions. Background from these sources is estimated to be 4, 4.3, and 2.8 kg-N/ha in the Adirondacks, mid-Appalachians, and Southern Blue Ridge, respectively.[73] Therefore, the scenario analyzed in this section focuses on anthropogenic NO_x emissions reductions.

Exhibit 42 shows historical and projected nationwide total NO_x emissions for the period 1980 to 2010 with and without implementation of Title IV. The emissions projections include Title I (i.e., reasonably achievable control technologies) and motor vehicle NO_x reductions mandated by Title II. The difference in the two projections is the 2 million ton per year reduction in utility NO_x emissions estimated to come from Title IV. Unlike utility SO_2 emissions, NO_x emissions are not capped by the CAAA.

As shown in Section 3.2.1, utilities and highway vehicles are each responsible for about one-third of nationwide emissions of NO_x and industrial sources for about one-sixth of nationwide NO_x emissions. Exhibits 43–45 show nitrogen deposition maps of the RADM region for each of these source categories in 1990. Deposition resulting from utility emissions is strongly concentrated in the Ohio Valley and falls away almost uniformly with distance. Industrial deposition is concentrated on the Gulf Coast, reflecting the concentration of high NO_x emitting industry in that area. Deposition from mobile sources is concentrated along the East Coast as a result of automobile emissions in urban areas. The principal contributors to deposition in the Southern Blue Ridge and mid-Appalachians are utility and industrial emissions. The Adirondacks are affected about equally by utility and mobile source emissions.

It is estimated that under Title II of the Act, mobile source emissions in 2010 in the eastern half of the United States will be reduced by about 15 percent from 1990 levels. Since mobile sources represent about one-third of total NO_x emissions, this reduction corresponds to a reduction in total NO_x of about 5 percent. Under Title IV, NO_x emissions rates from utility boilers will be reduced based on the degree of reduction available through the application of control technology. EPA estimates that implementation of these regulations will result in utility NO_x emissions in 2010 which are approximately 20 percent less than would have existed without Title IV. Implementation of Title I to achieve the ozone standard in the Northeast and other nonattainment areas is expected to involve significant reductions in NO_x emissions from utility, industrial, and mobile sources. These reductions are likely to be region specific.

[73] Van Sickle, J., M.R. Church. 1995. *Methods for Estimating the Relative Effects of Sulfur and Nitrogen Deposition on Surface Water Chemistry.* Environmental Research Laboratory, Corvallis, OR.

EXHIBIT 36. RADM-PREDICTED ANNUAL AVERAGE TOTAL SULFUR DEPOSITION (KG-S/HA) IN 2010 UNDER ADDITIONAL UTILITY SO_2 EMISSIONS REDUCTION SCENARIO

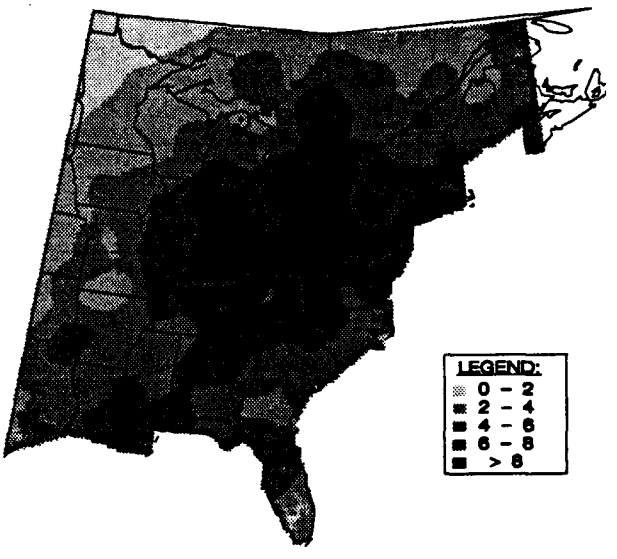


EXHIBIT 37. RADM-PREDICTED ANNUAL AVERAGE TOTAL SULFUR DEPOSITION (KG-S/HA) IN 2010 UNDER ADDITIONAL UTILITY AND INDUSTRIAL SO_2 EMISSIONS REDUCTION SCENARIO

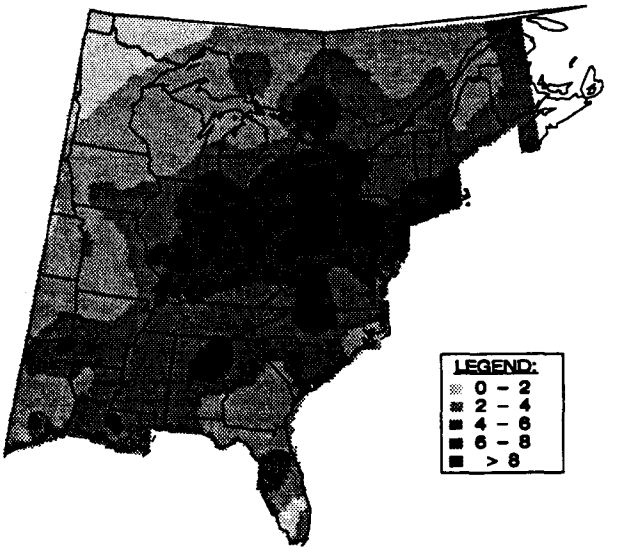


EXHIBIT 38. PERCENTAGE REDUCTIONS IN SULFUR DEPOSITION FROM POST-2010 FULL IMPLEMENTATION - UNDER ADDITIONAL UTILITY SO_2 REDUCTION SCENARIO

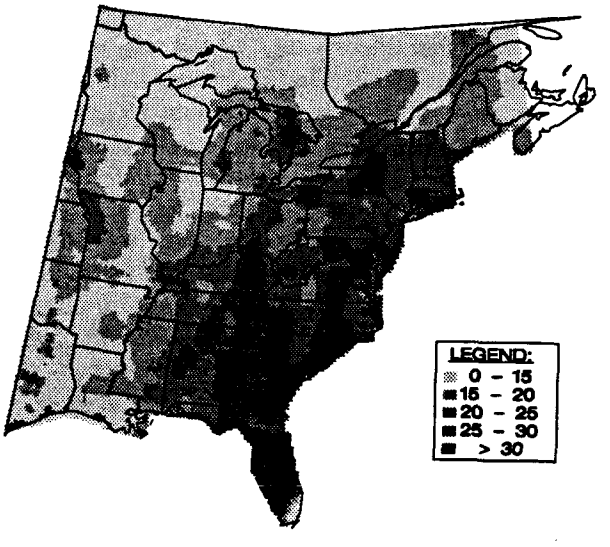


EXHIBIT 39. PERCENTAGE REDUCTIONS IN SULFUR DEPOSITION FROM POST-2010 FULL IMPLEMENTATION UNDER ADDITIONAL UTILITY AND INDUSTRIAL SO_2 REDUCTION SCENARIO

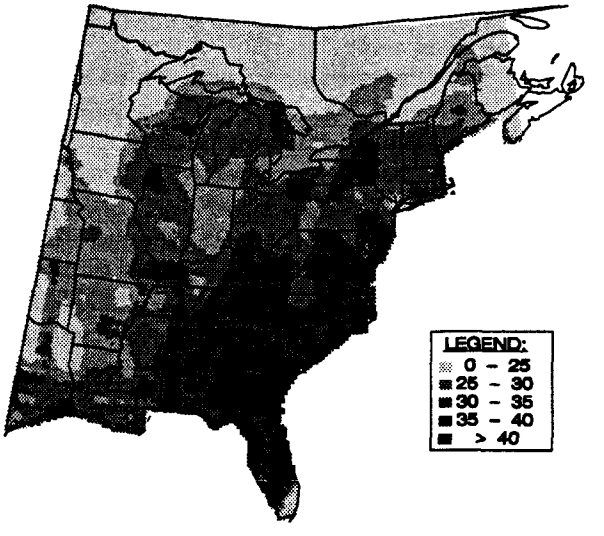


EXHIBIT 40. SULFUR DEPOSITION TO SENSITIVE REGIONS UNDER VARIOUS EMISSIONS SCENARIOS

Emissions Scenario	Annual Average Deposition Level (kg-S/ha)		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
1980	11.0	19.0	14.0
1985 NAPAP	9.8	17.0	13.0
Post-2010 full implementation	6.9	11.0	9.7
CAAA implementation plus additional utility SO_2 reduction	5.5	8.1	6.8
CAAA implementation plus additional utility and industrial SO_2 reduction	4.7	6.9	5.5

EXHIBIT 41. PERCENT REDUCTIONS IN SULFUR DEPOSITION TO SENSITIVE REGIONS FROM 1980 LEVELS UNDER VARIOUS EMISSIONS SCENARIOS

Emissions Scenario	Percent Reduction		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
Post-2010 full implementation	39	41	31
CAAA implementation plus additional utility SO_2 reduction	51	56	52
CAAA implementation plus additional utility and industrial SO_2 reduction	58	63	60

EXHIBIT 42. ESTIMATED U.S. NO_x EMISSIONS WITH AND WITHOUT TITLE IV FROM 1980 TO 2015

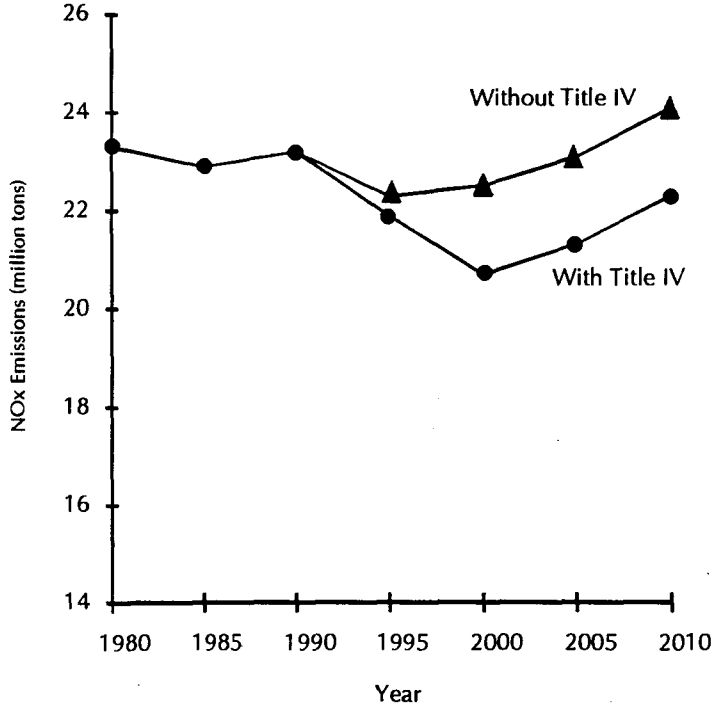


EXHIBIT 43. PERCENT CONTRIBUTION OF UTILITY SOURCES TO NITROGEN DEPOSITION IN 1990

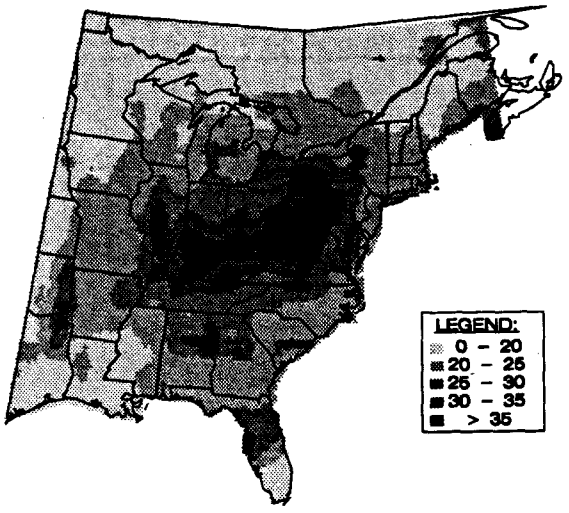
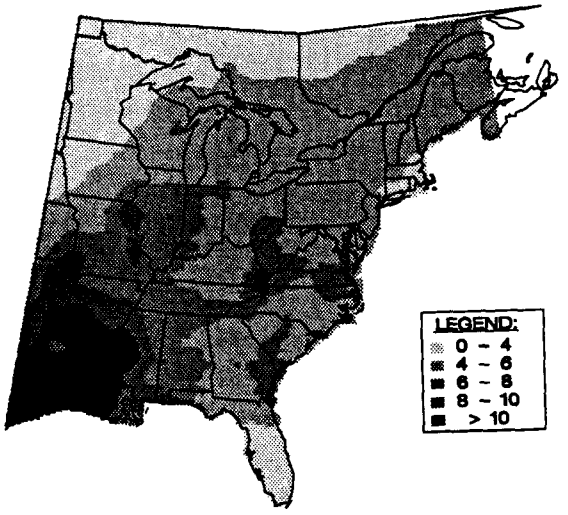
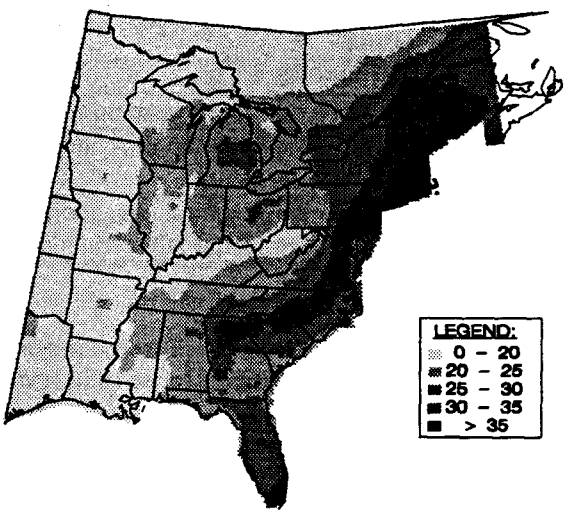


EXHIBIT 44. PERCENT CONTRIBUTION OF INDUSTRIAL SOURCES TO NITROGEN DEPOSITION IN 1990



A detailed inventory of NO_x emissions in the year 2010 suitable for RADM modeling which considered full implementation (all Titles) CAAA was not available for this report. As a scoping exercise for this report two emissions scenarios were used: the baseline 1990 Interim Inventory and an inventory in which NO_x emissions from industrial and utility sources is reduced by 50 percent from 1990 levels. This reduction inventory, as described in Section 3.4, corresponds to a 24 percent decrease in total

EXHIBIT 45. PERCENT CONTRIBUTION OF MOBILE SOURCES TO NITROGEN DEPOSITION IN 1990



NO_x emissions. Nitrogen deposition from ammonia was assumed to remain constant. Exhibits 46 and 47 are maps of nitrogen deposition from the 1990 Interim Inventory and from the utility and industrial emissions reduction scenario. Exhibit 48 is a map of percentage reductions in nitrogen deposition due to the control scenario. Exhibit 49 summarizes nitrogen deposition and percentage reductions for the baseline and control scenarios. Percentage reductions are less than for the similar SO_2 scenario for two reasons: ammonia emissions, which account for between one-fifth and one-quarter of nitrogen deposition in the eastern United States, are assumed to be constant and utility and industrial sources account for only about 50 percent of total NO_x emissions, whereas these categories account for 87 percent of SO_2 emissions. The greatest percentage reduction is found in the mid-Appalachians, followed by the Southern Blue Ridge, and then the Adirondacks, reflecting the relative importance of utility and industrial NO_x emissions to deposition in these regions.

3.6 EMISSIONS REDUCTIONS STRATEGIES TO ACHIEVE GEOGRAPHICALLY TARGETED SULFUR DEPOSITION LOADS

In the previous section deposition values were projected for nationwide emissions control scenarios. That is, similar to Title IV, the reductions resulted from control approaches which specified emissions reductions by source category not by geographic location. This section describes and analyzes geographically targeted emissions reductions to achieving deposition reductions. Analysis of

EXHIBIT 46. ANNUAL AVERAGE RADM TOTAL NITROGEN DEPOSITION (KG-N/HA) IN 1990

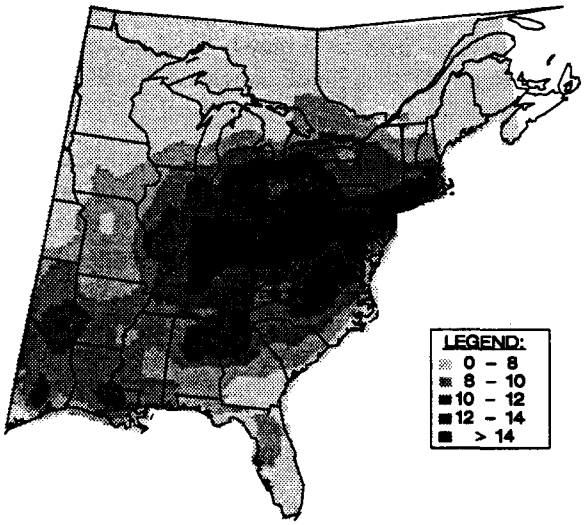


EXHIBIT 47. RADM-PREDICTED ANNUAL AVERAGE TOTAL NITROGEN DEPOSITION (KG-N/HA) UNDER UTILITY AND INDUSTRIAL NO_x EMISSIONS REDUCTIONS SCENARIO

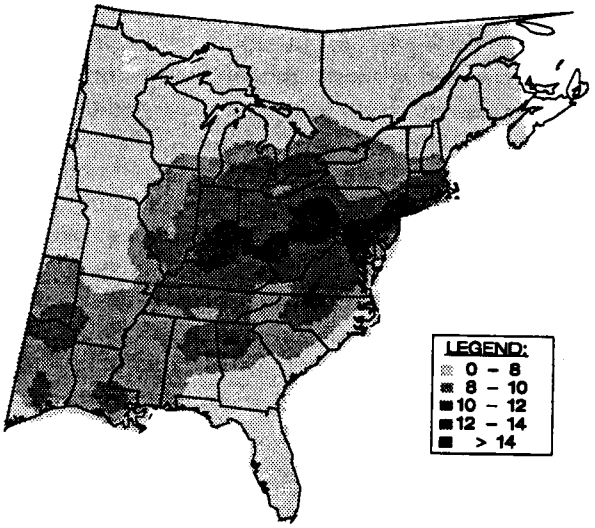


EXHIBIT 48. PERCENTAGE REDUCTIONS IN NITROGEN DEPOSITION UNDER UTILITY AND INDUSTRIAL NO_x EMISSIONS REDUCTIONS SCENARIO

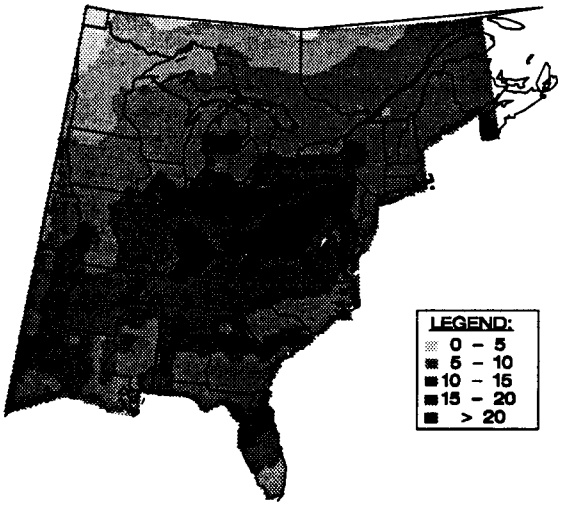


EXHIBIT 49. NITROGEN DEPOSITION TO SENSITIVE REGIONS UNDER BASE CASE AND ADDITIONAL UTILITY AND INDUSTRIAL NO_x EMISSIONS REDUCTION SCENARIO

Emissions Scenario	Annual Average Deposition Level (kg-N/ha)		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
1990 Base Case	9.5	14.3	11.9
Additional utility and industrial NO_x reductions from 1990 base case (% reduction from base case in parenthesis)	8.1 (14%)	11.3 (21%)	9.9 (16%)

these reductions relies on RADM source-receptor relationships to target source regions for emissions reductions needed to achieve a specified target load.

The assessment of geographically targeted reductions strategies relies on the ability of the RADM Tagged Engineering Model to identify the contribution of emissions from tagged source regions to deposition in selected target regions. This assessment is based on results for the 53 tagged regions shown in Exhibit 19. To illustrate the potential applicability of this geographic targeting, deposition goals for the three sensitive aquatic regions were selected to be equal to the deposition levels achieved by the source-category specific SO_2 reduction scenarios analyzed in Section 3.5. The maintenance load scenario is described in Exhibit 50.

As noted in Section 3.3, implementing Title IV will result in a higher proportion of sulfur deposition in sensitive aquatic regions coming from nearby sources in 2010 than was the case in 1985. At the same time, the top 10 emitting regions' contributions to deposition in those areas will decrease in importance from 1985 to 2010. To assess the feasibility of defining geographically targeted emissions reductions for given deposition targets, two potential scenarios were selected. The first limits the selection to obtaining the required emissions reductions from sources near a sensitive region. The other focuses on securing emissions reductions from those RADM subregions most responsible for deposition in a sensitive region.

Exhibit 40 lists the deposition level for each sensitive aquatic region achieved by a further 50 percent reduction in utility SO_2 emissions beyond the CAAA from utility sources in the United States and the deposition level achieved by a further 50 percent reduction in utility and industrial sources. These deposition levels were selected to illustrate target loads in order to compare nationwide and target emissions reductions. Exhibit 27 shows that in 2010 after implementation of the CAAA, local and contiguous sources will contribute 7.8 percent of deposition in the Adirondacks, 28 percent in the mid-Appalachians, and 26 percent in the Southern Blue Ridge. Thus, up to a point it should be feasible to develop geographically restricted targeted areas for emissions reductions in the mid-Appalachians and the Southern Blue Ridge as long as the reductions demanded are significant, such as 95 percent or greater. Because of the relatively smaller contribution of local sources to deposition in the Adirondacks, reductions in emissions from a large geographic area would be required to achieve targeted levels of deposition.

To achieve the same deposition levels as the scenario defined by a 50 percent reduction in utility SO_2 emissions beyond that achieved by the CAAA, targeted source regions were identified by sequentially removing 95 percent of the SO_2 utility emissions (remaining after implementation of Title IV) from each subregion until the deposition levels listed in Exhibit 40 were achieved. For the contiguous scenario, emissions were removed starting at the center of the sensitive region and continued outward until the deposition goal was reached. For the noncontiguous scenario, emissions were removed by subregion in order of contribution to deposition to the sensitive region.

Exhibits 51a and 51b show the results of targeted emissions reductions to achieve the same deposition as the 50 percent additional SO_2 utility case. The exhibits show that geographically targeted reductions can be achieved for all of the sensitive aquatic areas. As anticipated, it takes a larger number of tagged-regions and greater emissions reductions to achieve the target for the Adirondacks than for the other two regions. By comparing the emissions reductions required in the contiguous vs. non-contiguous scenarios, it is apparent that only in the Southern Blue Ridge are contiguous reductions more efficient, requiring 25 percent fewer emissions reductions. This difference for the Southern Blue Ridge can be attributed to the inclusion of RADM Subregion 51 (Northern Florida), a major emitting region, in the non-contiguous reductions. For the other two sensitive regions both contiguous and non-contiguous reductions rely essentially on the same geographic areas of the country. It is also interesting to note that the total emissions reductions to achieve all three target loads simultaneously are essentially equal and are less (i.e., amount of total emissions reductions) than 10 percent more efficient than a nationwide 50 percent reduction in utility SO_2 emissions.

EXHIBIT 50. SELECTION OF MAINTENANCE LOADS

Critical load definitions are founded on scientific determinations of quantitative pollutant loadings below which no significant harmful effects occur to critical ecological processes. Critical load definitions depend solely on inherent ecological properties. Target load definitions differ in that they incorporate social, policy, economic, and related considerations along with the scientific observations. An example of a possible target load would be a decision to regulate acidic deposition at levels adequate to maintain proportions of ANC≤50 μeq/l waters, roughly equivalent to pH≥6.5, at or below the proportions found during the 1984-85 National Surface Water Surveys (NSWS) for each of three regions in the eastern United States discussed here. Other possible goals for defining target loads could include, for example, restricting deposition to produce a reduction in the 1984-85 proportions of ANC≤ 50 μeq/l waters by a specific percentage or to some fixed proportion endpoint. Also, the definition could be expanded to include a larger geographical region.

For purposes of illustration, assume that social, policy, economic, scientific considerations led to a selection of the first of the above options as a generally acceptable goal for a target load: to limit sulfur deposition rates sufficiently to maintain proportions of target population surface waters having ANC≤ 50 μeq/l in these regions through the year 2040 at proportions no greater than those found for the same subpopulation by the 1984-85 NSWS. This maintenance load also would allow for a possible restoration of prior ANC levels and reduction in acidic conditions in some of these waters. The numeric proportions of target population waters with ANC≤50 μeq/l found in 1984-85 that would be used to evaluate attainment of this goal in each of the three regions are ≤55 percent in the Adirondacks, ≤27 percent in the Mid Appalachians, and ≤6 percent in the Southern Blue Ridge. It is important to note, however, that the percentages reported here represent sensitive subpopulations of the overall number of surface waters in those regions.

The Nitrogen Bounding Study (NBS) projections, described in detail in Chapter 2, can be used to determine sulfur deposition values necessary to attain this goal by locating these percentages on the NBS plots shown in Appendix B. For each region, projections of sulfur deposition loadings necessary to maintain the 1984-85 NSWS proportions of ANC≤50 μeq/l waters depends on the assumed time to nitrogen saturation for that region. For the purposes of this analysis, it has been assumed that nitrogen deposition rates will remain unchanged for the 1984-2040 period. In considering this approach, it is critical to recognize that, while the NBS modeling results are the best available information, there are significant uncertainties in the projected relationships (see Section 2.6.3). Consequently, the magnitude of the uncertainties in sulfur deposition maintenance loads used in this analysis cannot be quantified at this time.

Current scientific uncertainty does not allow quantifying the time to nitrogen saturation for any of the three sensitive regions nor for any other regions. However, it is reasonable to suggest that times to saturation do vary among regions due to differences in temperature, moisture, soil fertility, forest age, history of nitrogen deposition, and other variables. Watersheds in the Northeast have cooler annual temperatures, shorter growing seasons, and long histories of elevated nitrogen and sulfur deposition levels. Consequently, watersheds in the Adirondacks may include those having the shortest remaining times to nitrogen saturation. Watersheds in the Mid-Appalachians and Southern Blue Ridge Province may have longer remaining times to nitrogen saturation.

For illustrative purposes in this analysis, if the time to nitrogen saturation is between 75 and 150 years in the Mid-Appalachians, and between 200 and 300 years in the SBRP, then a sulfur deposition load of about 5 kg/ha/yr is projected by the NBS results as potentially maintaining surface waters with ANC≤ 50 μeq/l at 1984-85 proportions. NBS modeling suggests that for a time to nitrogen saturation for the Adirondacks of between 25 and 75 years, a greater than 50 percent reduction in both sulfur and nitrogen may be necessary to maintain the 1984 proportion of ANC≤50 μeq/l lakes; however, a 5 kg/ha/yr sulfur load would likely provide some benefits.

This example of a loadings approach (i.e., maintenance load) concentrates only on sulfur deposition, while nitrogen deposition is held constant. However, NBS results for all three regions indicate that reducing nitrogen deposition rates is projected to provide likely benefits in reducing proportions of ANC ≤0 μeq/l and ANC≤50 μeq/l surface waters that may equal or exceed the potential benefits obtainable from reducing sulfur deposition alone. The amount of benefit would depend on the actual amount of reduction in sulfur and nitrogen deposition obtained, and on the actual time to watershed nitrogen saturation within each region. Any efforts to develop acid deposition standards would likely include both sulfur and nitrogen.

EXHIBIT 51A. GEOGRAPHICALLY TARGETED ADDITIONAL UTILITY SO_2 REDUCTION IN CONTIGUOUS RADM SUBREGIONS

	Sensitive Region			All Three Receptor Regions	Nationwide Utility
	Adirondacks	Mid-Appalachians	Southern Blue Ridge		
Deposition	5.5 kg-S/ha	8.1 kg-S/ha	6.8 kg-S/ha	—	—
Subregions	45,44,5,4,2,3,9, 11,12,14,7,8,10, 13,15,18,19,20,22	13,19,28,20, 21,27,15,22	29,30,31,39,38, 37,28,21,23,27, 36,32,33,40	—	—
SO_2 Emissions Reduction (tons)	3,018,000	1,952,000	1,508,000	4,526,000[a]	5,047,000

[a] This emissions total was derived without double counting those subregions contributing to deposition in more than one receptor region.

EXHIBIT 51B. GEOGRAPHICALLY TARGETED ADDITIONAL UTILITY SO_2 REDUCTION IN MAJOR RADM SUBREGIONS CONTRIBUTING TO DEPOSITION (NOT CONTIGUOUS)

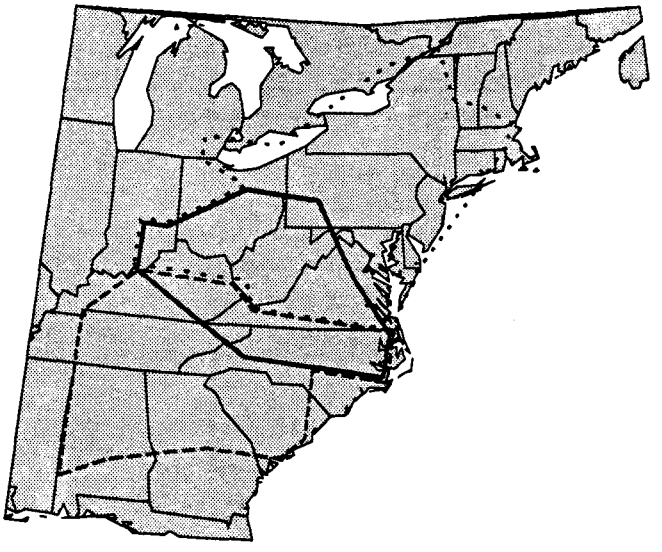
	Sensitive Region			All Three Receptor Regions	Nationwide Utility
	Adirondacks	Mid-Appalachians	Southern Blue Ridge		
Deposition	5.5 kg-S/ha	8.1 kg-S/ha	6.8 kg-S/ha	—	—
Subregions	15,13,22,20, 14,7,10,12,25, 3,9,5,2,17,44	13,20,15, 22,28,27,10	31,29,39,38,28, 37,40,51,20,22	—	—
SO_2 Emissions Reduction (tons)	3,160,000	2,080,000	2,081,000	4,658,000[a]	5,047,000

[a] This emissions total was derived without double counting those subregions contributing to deposition in more than one receptor region.

Exhibit 52 is a map of the geographically targeted reductions for the contiguous reductions for all three receptor regions. RADM subregions required for the Adirondacks (indicated by short dashes) extend from the Canadian border south through Virginia and Kentucky and from the Eastern seaboard west to the middle of Indiana. Source regions for the mid-Appalachians (solid line) are fairly symmetric around the region and extent from the middle of Ohio south through central North Carolina and west from the North Carolina Coast to the middle of Indiana. For the Southern Blue Ridge source regions (longer dashed lines) include most of North and South Carolina, Kentucky, Tennessee, and Alabama and the northern half of Georgia. The map shows the striking overlap between tagged regions required for achievement of the target load in the mid-Appalachians and the other two source regions and the lack of overlap between the Adirondack and Southern Blue Ridge source regions. Achieving the target loads in the Adirondacks and Southern Blue Ridge would also achieve the target load in the mid-Appalachians.

A similar analysis was conducted to determine if the maintenance loads developed for illustrative purposes and loads defined by the deposition levels achieved by the nationwide 50 percent utility plus industrial SO_2 emissions reduction could be achieved by targeting only utility emissions in the 53 tagged subregions. It was only possible to achieve the deposition targets in the mid-Appalachians. It was possible to achieve the maintenance load in the Adirondacks, but not in the mid-Appalachians or the Southern Blue Ridge, when only considering 95 percent reductions of utility emissions in the targeted regions. Thus, tar-

EXHIBIT 52. MAP OF EXTENT OF CONTIGUOUS GEOGRAPHIC REGIONS FOR ACHIEVING TARGETED DEPOSITION LOADS EQUIVALENT TO ADDITIONAL NATIONWIDE UTILITY SO_2 REDUCTIONS



geting scenarios that included industrial emissions reductions were then analyzed.

For the 50 percent utility and industry SO_2 reductions beyond the post 2010 full implementation scenario, targeted source subregions were identified by sequentially removing 95 percent of the SO_2 major source (utility plus large industrial sources) emissions from each subregion. Results are shown in Exhibits 53a and 53b. It appears feasible to have geographically targeted controls if reductions are from both utility and industrial sources. For these targets, there is little geographic "efficiency" between constraining the tagged subregions to be contiguous or focusing on the regions most responsible for deposition. Thirty-one emissions subregions are included in the former case for all three sensitive receptor regions and 29 in the latter. As shown in Exhibit 54 the tagged subregions cover the same geographical expanse as those involved in utility reduction targeted scenario (compare Exhibit 52). The principal difference is that the overlap among regions is more extensive with reductions in some source regions required to achieve target loads in all three sensitive regions. Again, emissions reductions from sources in the western part of the RADM domain are not required.

For the maintenance load analysis, a 95 percent reduction in major source emissions was used. The results for the case focusing on emissions reductions from regions most responsible for deposition are shown in Exhibit 55. Compared to the number of tagged emissions regions shown in Exhibit 53b, the number is somewhat less for the Adirondacks, somewhat more for the Southern Blue Ridge, and almost 3 times larger for the mid-Appalachians. Nevertheless, the total number of tagged regions is comparable, 31 for the 50 percent utility plus industrial source scenario and 33 for the maintenance load scenario). Two-thirds of the subregions contributing to the Adirondacks and two-thirds of the subregions contributing to the Southern Blue Ridge also are major sources of deposition in the mid-Appalachians. (A similar analysis using only contiguous subregions shows a greater than 90 percent overlap between the Southern Blue Ridge and mid-Appalachians). There is no overlap of the two sets of subregions identified for the Adirondacks and the Southern Blue Ridge. Thus, these regions could be individually targeted; however, attempting to achieve the maintenance load for the mid-Appalachians may be best done as part of a strategy to achieve it for all three sensitive regions at the same time. Using a maintenance load chosen for illustrative purposes in this report, it appears not to be very advantageous to geographically target regions individually to achieve a particular load.

EXHIBIT 53A. GEOGRAPHICALLY TARGETED ADDITIONAL UTILITY AND INDUSTRIAL SO_2 REDUCTION IN CONTIGUOUS RADM SUBREGIONS

	Sensitive Region		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
Deposition	4.7 kg-S/ha	6.9 kg-S/ha	5.5 kg-S/ha
Subregions	45,44,5,4,2,3,9, 11,12,14,8,10,13, 15,7,18,20,22	13,19,20,10, 15,28,27,18,22	29,30,31,39,38, 37,28,21,19,36,27, 15,20,22,23,40

EXHIBIT 53B. GEOGRAPHICALLY TARGETED ADDITIONAL UTILITY AND INDUSTRIAL SO_2 REDUCTION IN MAJOR RADM SUBREGIONS CONTRIBUTING TO DEPOSITION (NOT CONTIGUOUS)

	Sensitive Region		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
Deposition	4.7 kg-S/ha	6.9 kg-S/ha	5.5 kg-S/ha
Subregions	15,13,5,14,7,20, 22,44,10,12,45, 17,9,25,26,3	13,20,15,22,19, 28,27,18,10	29,31,39,38,37, 28,40,20,51,27, 21,30,22,15,25

EXHIBIT 54. EXTENT OF CONTIGUOUS GEOGRAPHIC REGIONS FOR ACHIEVING TARGETED DEPOSITION LOADS EQUIVALENT TO ADDITIONAL NATIONWIDE UTILITY AND INDUSTRIAL SO_2 REDUCTIONS

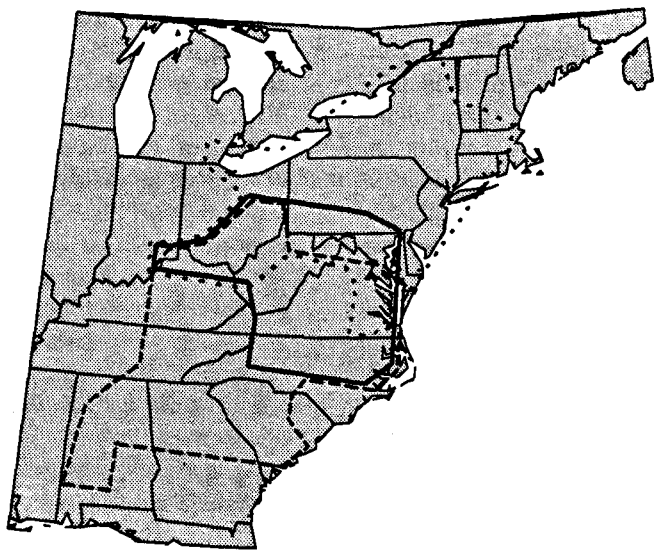


EXHIBIT 55. GEOGRAPHICALLY TARGETED REDUCTIONS WITH A MAINTENANCE LOAD OF 5 KG-S/HA IN MAJOR RADM SUBREGIONS CONTRIBUTING TO DEPOSITION (NOT CONTIGUOUS)

	Sensitive Region		
	Adirondacks	Mid-Appalachians	Southern Blue Ridge
Subregions	15,13,5,14,7,20, 22,44,10,12,45,17	13,20,15,22,19,28, 27,10,18,31,21,12, 25,14,37,39,29,26, 7,51,34,32,23,9	29,31,39,38,37,28,40, 20,51,27,21,30, 22,15,25,41,32,36

CHAPTER 4

POTENTIAL BENEFITS OF AN ACIDIC DEPOSITION STANDARD ON VISIBILITY, HUMAN HEALTH, MATERIAL, AND CULTURAL RESOURCES

4.1 INTRODUCTION

Chapter 2 of this report focused on the effects of acidic deposition on sensitive aquatic and terrestrial resources. This chapter describes how an acid deposition standard, in this case aquatics-based, could improve visibility, protect human health, and preserve material resources of functional and cultural importance.

4.2 RELATIONSHIP OF VISIBILITY TO ACIDIC DEPOSITION

In certain areas of the United States, visibility is a significant environmental indicator of air quality. Visibility impairment and subsequent improvement is therefore a strong measure of effectiveness and benefits. This section identifies regions in the United States subject to visibility degradation and describes how these areas could benefit from an acid deposition standard that, in this case, is designed to protect sensitive aquatic resources.

4.2.1 Visibility Impairment

Visibility refers to the degree to which the atmosphere is transparent to visible light. Fine particles in the atmosphere absorb and scatter light, thereby limiting visual range, decreasing color discrimination, and obscuring details of distant objects. Impairment of visibility depends on several factors, especially the size and composition of particles in the viewing path. Some gases absorb visible light and can impair visibility. Visibility is also affected by the angle of sunlight and so varies with time of day and season. Humidity can reduce visibility when hygroscopic particles absorb water and increase in size; larger particles scatter more light. Thus, natural visibility in the humid East is generally poorer than in the more arid West.

Visibility can be impaired by natural and anthropogenic sources. Natural sources include fog, precipitation, sea mist, windblown dust, volcanic emissions, and forest fires. Visibility impairment from these sources varies by season and meteorological condition. Anthropogenic sources include gaseous and particulate emissions from stationary and mobile sources. Most visibility impairment can be traced to one gas, nitrogen dioxide, and five particulate substances: sulfates, nitrates, organics, elemental carbon, and soil dust.

The National Academy of Sciences (NAS) estimated the contribution of anthropogenic air pollutants to visibility impairment in three areas of the country: the East (i.e., states east of the Mississippi), the Southwest (i.e., California, Nevada, Arizona, New Mexico, Utah, and Colorado), and the Northwest (i.e., Oregon, Washington, and Idaho).[74] Exhibit 56 summarizes findings for rural regions in each area. NAS also calculated that anthropogenic sources are responsible for seven-eighths of the visibility impairment in the East, five-eighths in the Northwest, and three-eights in the Southwest.

EXHIBIT 56. ANTHROPOGENIC CONTRIBUTIONS TO VISIBILITY IMPAIRMENT[74]

Contaminant	Percent		
	East	Southwest	Northwest
Sulfates	65	39	33
Organics	14	18	28
Elemental Carbon	11	14	15
Suspended Dust	2	15	7
Nitrates	5	9	13
Nitrogen Dioxide	3	5	4

The exhibit clearly indicates that most visibility impairment in the East is caused by sulfates (transformation products of sulfur dioxide, the majority of which is emitted from power plants). No single source category dominates visibility impairment in the West, although sulfur compounds play a significant role. In relatively clean areas of the West, small increases in pollutant levels can markedly degrade visibility. Thus, visibility in

[74] Committee on Haze in National Parks and Wilderness Areas. 1993. *Protecting Visibility in National Parks and Wilderness Areas.* National Research Council and National Academy of Sciences, Washington, DC.

Class I areas in the West is especially sensitive to increased levels of pollution.

4.2.2 Visibility Protection Laws and Class I Areas

Section 169A of the Clean Air Act (CAA) of 1977 established as a national goal "the prevention of any future and the remedying of any existing impairment of visibility in mandatory Class I areas which impairment results from man-made air pollution." Class I federal areas are defined in CAA Section 162(a) as international parks, national wilderness and memorial parks exceeding 5,000 acres, and national parks exceeding 6,000 acres in existence in 1977. EPA, in conjunction with the Department of the Interior (DOI), has designated 158 mandatory Class I areas where visibility is important.

States that either have Class I areas or contain sources that may contribute to visibility impairment of these areas are required to include in their state implementation plans (SIPs) a long-term strategy for making reasonable progress toward reducing impairment. Major stationary sources reasonably expected to contribute to visibility impairment in a Class I area must install best available retrofit technology.

The prevention of significant deterioration (PSD) provision in Sections 160–169 of the CAA also applies to visibility protection. The PSD program, which is directed toward new sources, requires that major emitting facilities seeking to locate in clean-air areas (i.e., areas meeting the National Ambient Air Quality Standard [NAAQS] for a particular pollutant) use best available control technology (BACT). The source must also comply with air quality increments that specify the maximum permissible increase in ambient pollutant levels for SO_2, NO_2, and particulate matter. Class I areas are further protected by the designation of Air Quality Related Values (AQRV) for several parameters, including visibility. In addition to complying with BACT and increment requirements, new sources must demonstrate that they will not adversely affect an area's AQRV.

When the PSD program was created in 1977, large national parks and wildernesses were designated as Class I areas to provide them with special air quality protection. Other parks and wilderness areas have been designated Class I in succeeding years. About two-thirds of the current Class I areas are west of the Mississippi. Nearly one-quarter are located in four southwestern states: Utah, Colorado, Arizona, and New Mexico. Monitoring visibility conditions at some sites was initiated by the National Weather Service in 1978. At approximately 43 other sites, visibility monitoring began in 1987 and continues under a multi-agency program called the Interagency Monitoring of Protected Visual Environments (IMPROVE). A rulemaking effort on regional haze protection recently initiated by EPA will further examine visibility impacts on and protection of Class I areas.

4.2.3 Visibility Metrics and the Projected Impact of the CAAA on Visibility

No standard or EPA-approved method for measuring optical air quality exists. Visibility has been measured and reported in several ways. Standard visual range is based on human perception of a large black object placed in the sky and is reported in kilometers or miles. A more scientific measure of visibility impairment is light extinction. An extinction coefficient is proportional to the attenuation of light per unit distance due to absorption and scattering of light by particles or gases. Extinction coefficients are a function of particle size and shape and the gaseous chemicals present. A third, recently developed measure is the deciview scale (analogous to the decibel scale for sound), which provides a haziness index designed to be linear to humanly perceived changes in visibility caused solely by air quality changes. The deciview (dv) scale is near zero for pristine atmospheric conditions and increases as visibility degrades; a 1 dv change corresponds to a 10 percent change in light extinction and approximates a minimum, commonly observable visibility change.

Several recent visibility studies have been conducted to assess the impact of the CAAA on visibility improvement; some analyses specifically assessed the impact of Title IV.

Eastern United States

A recent analysis compared standard visual range with and without Title IV of the CAAA to assess economic benefits of improvements in visibility.[75] The visual range maps (Exhibits 57 and 58) illus-

[75] Chestnut, L.G., R.L. Dennis, and D.A. Latimer. 1994. Economic benefits of improvements in visibility: Acid rain provisions of the 1990 Clean Air Act Amendments. Presented at *Aerosols and Atmospheric Optics: Radiation Balance and Visual Air* (continued)

EXHIBIT 57: ANNUAL AVERAGE VISUAL RANGE (KM) PROJECTED FOR 2010 WITHOUT TITLE IV: 50TH-PERCENTILE VISIBILITY

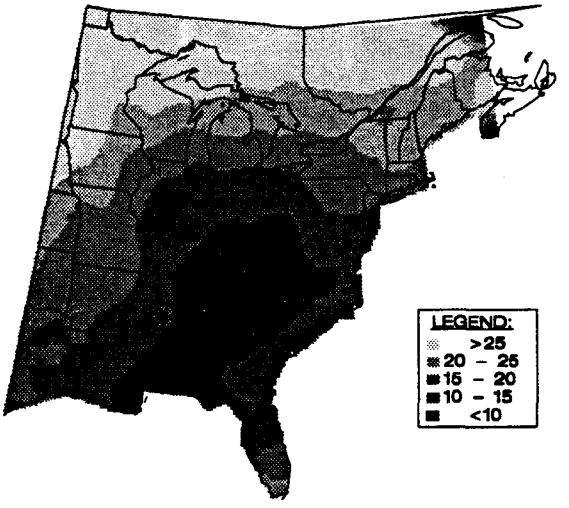
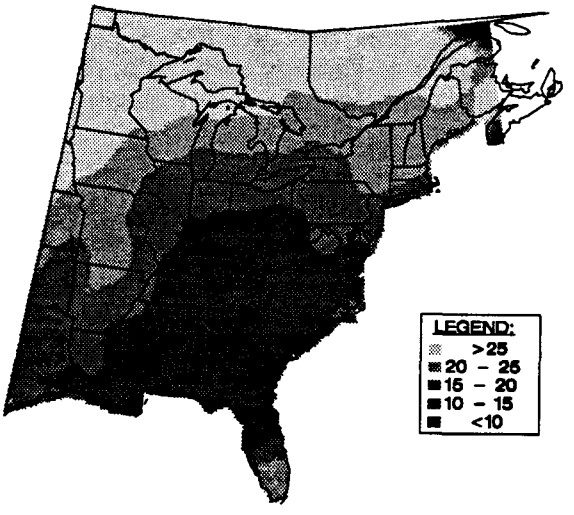


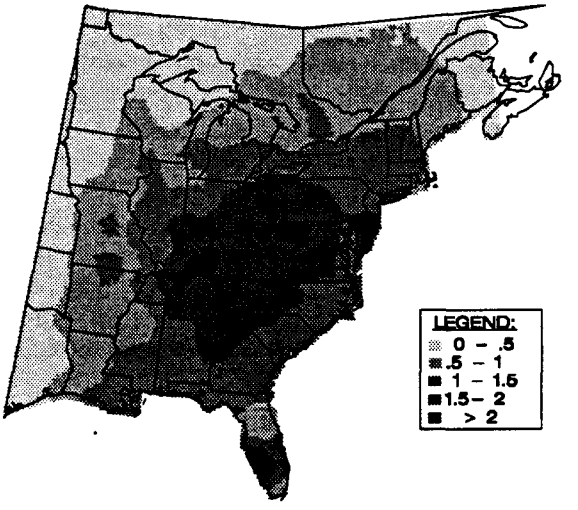
EXHIBIT 58. ANNUAL AVERAGE VISUAL RANGE (KM) PROJECTED FOR 2010 WITH TITLE IV, INCLUDING TRADING: 50TH-PERCENTILE VISIBILITY



trate impressive changes in visibility associated with Title IV. Although results are preliminary, the economic analysis indicates potentially significant monetary benefits to residential areas of 31 eastern states in the United States and to national parks in the southeastern United States.

An analysis was conducted for this study to compare current and future perceptible visibility degradation in the East, assuming implementation of Title IV in the year 2010. The assessment indicated a noticeable improvement in visibility across the eastern United States (Exhibit 59) from the 1980 base year, with most of the change occurring in the warm seasons.

EXHIBIT 59. ANNUAL AVERAGE IMPROVEMENT IN 50TH-PERCENTILE VISIBILITY (DV) FROM 1980 TO 2010 WITH TITLE IV, INCLUDING TRADING



A 1993 EPA Report to Congress presented visibility improvements to Class I areas that could be expected to accompany implementation of the 1990 CAAA.[76] The analysis evaluated impacts of control provisions for NO_x, SO_2, and particulate matter by assuming implementation of Titles I, II, and IV of the CAAA. Exhibit 60 lists specific provisions of each title.

Because sulfates dominate visibility impairment in the East, and no single chemical species dominates in the Southwest, EPA modeled each region sepa-

Quality, Air & Waste Management Association International Specialty Conference, Snowbird, Utah, September 30.

[76] Office of Air Quality Planning and Standards. October 1993. *Effects of the 1990 Clean Air Act Amendments on Visibility in Class I Areas: An EPA Report to Congress.* U.S. Environmental Protection Agency, Washington, DC.

EXHIBIT 60. SPECIFIC PROVISIONS OF TITLES I, II, AND IV

Title I	◆ Application of reasonably available control technology (RACT) NO_x control for ozone-moderate areas (or worse) and ozone transport regions ◆ Enhanced motor vehicle inspection and maintenance (I&M) for areas with conditions classed as ozone serious (or worse) and carbon monoxide-moderate (or worse) ◆ New Source Performance Standards (NSPSs) for NO_x
Title II	◆ 1995 tailpipe standards for NO_x reduction ◆ Using oxygenated fuels in nonattainment areas for carbon monoxide
Title IV	◆ Implementation of Phase I and II SO_2 limits, where emissions are based on projections from the Coal and Electric Utilities Model for the EPA Regulatory Impact Analysis (RIA) ◆ Implementation of NO_x controls

rately. EPA used the Regional Acid Deposition Model (RADM) post-processor (EM-VIS) to calculate visibility for each RADM cell in 1985 and 2010. The 1985 NAPAP emissions inventory was used as the basis for 1985 values. For the year 2010, implementation of Title IV was assumed, but without SO_2 emissions trading, because an emissions scenario depicting trading was unavailable at that time. (Note, however, that the analysis of the environmental impact of trading allowances, described in Section 3.5.1, found only minimal differences in deposition due to trading.) Reductions in Canadian SO_2 emissions predicted by Environment Canada as part of the 1990 NAPAP Integrated Assessment were also used in the 2010 modeling.

Extensive comparisons of percent change in visual range were made using annual average change and 90th-percentile worst days (i.e., only 10 percent of days have worse visibility) and 10th-percentile best days (i.e., only 10 percent of days have better visibility). For 50th-percentile visibility days (half the days have better and half worse visibility), the percent increase in visual range in the East ranged from 10 to 20 percent in Florida, New England, and just east of the Mississippi to 30 to 40 percent in the mid-Appalachians and the Ohio Valley. The largest improvement in 50th-percentile visibility range in Class I areas was predicted to be in Shenandoah National Park in the mid-Appalachians.

Western United States

To illustrate the visibility impact on western Class I areas in the 1993 Report to Congress, EPA conducted a comprehensive analysis of changes in visual range resulting from implementation of the 1990 CAAA, including the development of emissions inventories for anthropogenic sources of NO_x, SO_x, and particulates for 1988, a 2005 base-case scenario, and a 2005 CAAA-implemented scenario.[77] The 1985 NAPAP emissions inventory served as the basis for the annual inventories. Electric utility emissions estimates in the NAPAP inventory were replaced by emissions from the more up-to-date National Allowance Data Base (NADB). Emissions estimates for two large smelters near the border in Mexico were also included in the inventories. These emissions inventories were used to model projected air quality changes from 1988 to 2005. (EPA's 1993 Visibility Report to Congress contains a detailed description of models used and assumptions made.)

Comparing emissions for SO_2, NO_x, and fine particulates revealed only minor differences in the total emissions of each species between 1988 and 2005. Emissions for the three scenarios by source category for SO_2 and NO_x show that SO_2 emissions are equally distributed among area, utility, and other point sources (e.g., smelters, refineries, and pulp mills). Of the 100,000-ton decrease in utility emissions between 1988 and 2005, over half is a result of scrubbing at the Navaho station. NO_x emissions are primarily attributable to motor vehicles and area sources. Mobile sources account for most of the decrease in NO_x emissions, whereas utility emissions increase slightly.

[77] Visibility modeling described here was conducted before this study was initiated; thus, inventories used are slightly different from those described in Chapter 3. Differences in the inventories should not significantly affect qualitative conclusions, however.

Three-hour average visual range estimates were developed for representative Class I areas in six geographic regions: Central Coast (California), Sierra, Southern California, Desert Southwest, Golden Circle (Arizona), and Rockies. Exhibit 61 summarizes annual visual range estimates for each inventory scenario calculated from the 3-hour averages.

Exhibit 61 indicates that neither the growth in emissions between 1988 and 2005 nor implementation of the 1990 CAAA at sources in the Southwest will have an appreciable effect on visual range in Class I areas. The insensitivity of predicted visibility changes between the years 1988 and 2005, even with implementation of the 1990 CAAA in the latter year, is clearly consistent with the relatively small changes in SO_2, NO_x, and particulates during this period.

EXHIBIT 61. AVERAGE ANNUAL VISUAL RANGE ESTIMATES FOR REPRESENTATIVE CLASS I AREAS IN THE SOUTHWEST

Geographic Region	Representative Class I Areas(s)	Visual Range (km)	
		1988	2005 CAAA
Central Coast	Pinnacles	96	94
Sierra	Yosemite	104	101
Southern California	San Gorgonio	68	66
Desert Southwest	Chiricahua	118	115
Golden Circle	Grand Canyon	134	132
	Arches	116	115
Rockies	Rocky Mountain	121	120
	Bandelier	119	116

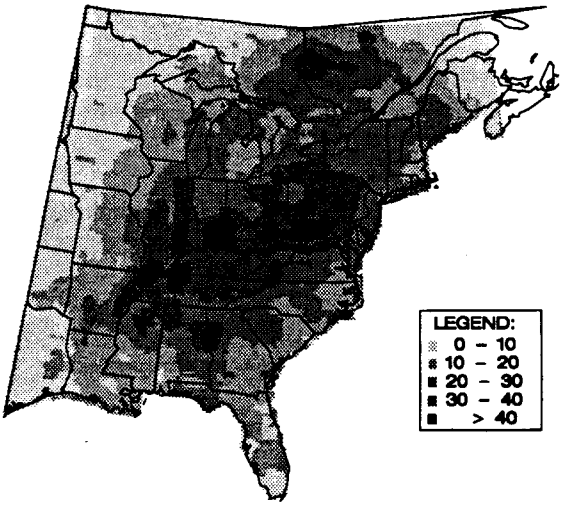
The study conducted by EPA for Class I areas in the Southwest demonstrates that no single pollutant or source category is responsible for most of the visibility impairment in that region. Thus, while an acid deposition standard could reduce ambient sulfate, nitrate, or NO_2 levels, projection of potential improvements in visibility for specific Class I areas would require additional model analysis.

4.2.4 Potential Impact of an Acidic Deposition Standard on Visibility

For this study, visibility in the East was calculated using the RADM EM-VIS model for two SO_2 emissions scenarios described in Chapter 3. Visible ranges for the post-2010 full implementation scenario and for the additional utility and industrial SO_2 reduction scenario (approximately 44 percent decrease in SO_2 emissions beyond CAAA reductions) were calculated for 90th-percentile worst days. Maps in Exhibits 62 and 63 show percentage changes in annual average visibility for these two scenarios between 1985 and 2010. To assess the impact of changes in visibility due only to decreases in ambient sulfate concentration, visibility impairment from other ambient species remained constant in the models.

The greatest improvements in visual range between 1985 and the baseline scenario in 2010 lie in a band from northern Mississippi to southwestern New York State. Improvements in visibility for Class I areas in the mid-Atlantic region, which includes the Great Smoky Mountains and the Shenandoah Valley, range between 30 percent and more than 40 percent. For the additional SO_2 reduction case, improvements in visual range of greater than a factor of two are predicted for these key mid-Atlantic areas. Increases in visual range of 60 to 100 percent (i.e., the ability to see twice as far) are predicted for coastal areas and New England.

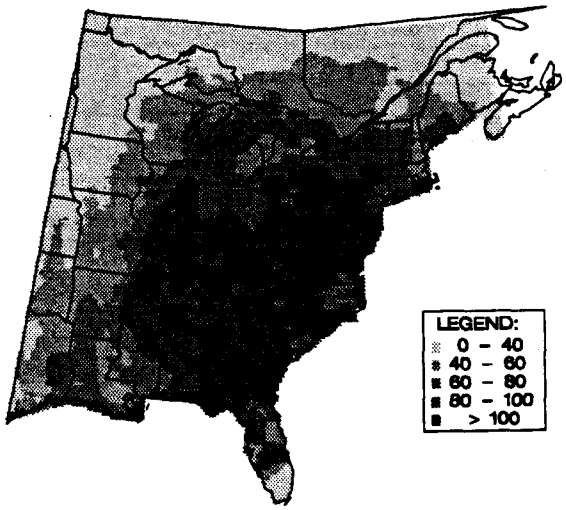
EXHIBIT 62. PERCENT INCREASE IN VISUAL RANGE FROM 1985 TO 2010 WITH FULL CAAA IMPLEMENTATION



4.3 RELATIONSHIP OF HUMAN HEALTH TO ACIDIC DEPOSITION

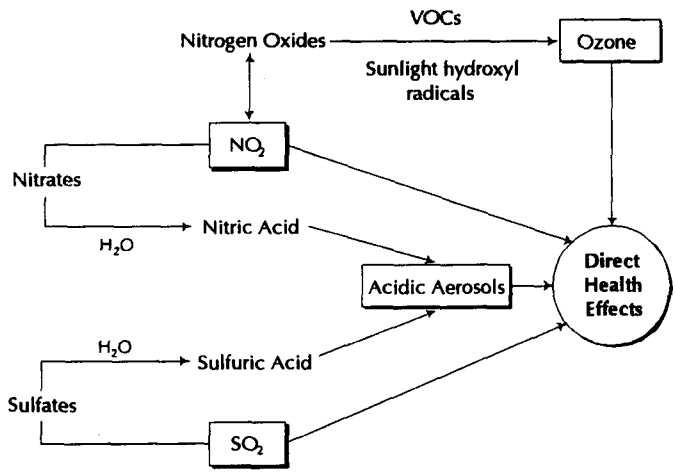
Exposure to SO_2, particulate matter (including acidic aerosols), NO_2, and ozone (O_3) in ambient air can cause adverse health effects. (Ozone is a

EXHIBIT 63. PERCENT INCREASE IN VISUAL RANGE FROM 1985 TO 2010 WITH ADDITIONAL SO_2 REDUCTION BEYOND CAAA



related concern for acidic emissions and deposition standards because NO_2 is a major precursor in O_3 formation.) Possible health effects related to acidic deposition and its precursors are quite complex because of the variety of pollutants, possible routes of exposure, and mechanisms involved (Exhibit 64).

EXHIBIT 64. RELATIONSHIP OF ACIDIC DEPOSITION PROCESSES TO HEALTH EFFECTS



The potential health benefits derived from reductions in fine particulate mass, SO_2, and NO_x emissions resulting from Title IV as well as additional reductions beyond the CAAA have not been modeled for this study. Several health issues are briefly outlined here, however, because of the potential benefit of an acid deposition standard. Current applicable standards include National Ambient Air Quality Standards (NAAQS) for SO_2, NO_2, and O_3. The 10-million ton SO_2 emissions reduction from 1980 levels under Title IV is expected to result in human health benefits and potentially high monetary savings due to reduced mortality and morbidity effects associated with SO_2 and fine particle exposures.

The following subsection summarizes health effects and potential risks associated with airborne acidic pollutants. Current knowledge on possible future risks to human health associated with changes in acidic deposition rates is summarized in the second subsection.

Several respiratory problems can be caused by ambient air concentrations of SO_2, particulate matter (including acidic aerosols), NO_2, and O_3 (separately and in combination). Effects include chronic bronchitis, bronchoconstriction, other pulmonary function impairments, chest discomfort, cough, lung inflammation, increased incidence of infectious respiratory disease, and increased mortality rates. The elderly, the very young, and individuals with pre-existing respiratory diseases, such as asthma, are at greatest risk and would benefit most from reductions in the atmospheric concentrations of these pollutants.

Under Sections 108 and 109 of the CAAA, EPA establishes primary NAAQSs, which protect the most sensitive segments of the population, with an adequate margin of safety. The additional emissions reductions achieved by an acid deposition standard would facilitate the attainment and maintenance of the primary NAAQS established under Sections 108 and 109 of the Act.

A number of recent epidemiological studies have associated particle pollution with excess mortality and morbidity at levels below the existing 24-hour particulate matter NAAQS. For example, a decade-long, six-city study provided evidence of a strong association between fine particulates, including sulfate, and mortality in humans and also indicated that acidic aerosol concentrations were directly associated with increased prevalence

of bronchitis in children.[78] Clinical studies suggest that asthmatics may exhibit sensitivities to short-term exposures to acidic aerosols. As a result, the EPA has initiated the review of the air quality criteria and standards for particulate matter, including acidic aerosols. Additional research shows that sulfate aerosols comprise the majority of acidic aerosols in ambient air and a large share of total ambient inhalable particulate matter in the eastern United States.[79]

Based on the available data, many in the scientific community believe that if the mortality and morbidity effects observed in these studies are causal, the agent(s) is more likely to be fine particles (≤2.5 μm) than coarse particles (2.5 to 10 μm). If it is determined, after completion of the ongoing review, that a new fine particle standard(s) is appropriate, the associated control strategies will focus on the control of the precursors (e.g., SO_2, NO_x, ammonia, and condensible hydrocarbons) to secondary fine particles. Thus, the emissions reduction objectives of an acid deposition standard would be compatible with those of a potential new fine particle NAAQS.

Insofar as acidic SO_4^{2-} trends roughly parallel total SO_4^{2-} trends, NAPAP estimated that between 2000 and 2020, the region generally incorporating the states of Ohio, Indiana, West Virginia, Pennsylvania, New Jersey, Maryland, Virginia, North Carolina, Kentucky, Tennessee, and northern Georgia could experience the greatest decrease in acidic sulfate levels from implementation of the CAAA.[80] The upper Midwest (Michigan and Wisconsin) and the upper Northeast (Maine and New Hampshire), which had lower ambient 1-hour sulfate levels, are estimated to have only slightly improved atmospheric concentrations in the years 2000 and 2020 under this scenario. Several ongoing benefit assessments will address the extent of monetary health benefits associated with implementation of Title IV.

With respect to NO_2, no area of the United States presently exceeds the NAAQS of 0.053 ppm, annual average. The attainment of the annual standard also significantly limits the likelihood and magnitude of short-term 1-hour peak NO_2 levels. NO_2 and its transformation products, however, are precursors to O_3 formation. Consequently, reductions in NO_2 or NO_x emissions are key components of the O_3 control strategies.

4.4 RELATIONSHIP OF MATERIALS DAMAGE AND CULTURAL RESOURCES TO ACIDIC DEPOSITION

All materials exposed to the outdoor environment are subject to degradation caused by natural weathering processes involving moisture, heat, oxygen, solar radiation, bacteria, and fungi. Adverse effects from these processes can be accelerated by deposition of wet and dry acidic air pollutants. Several NAPAP reports, including the State of the Science and Technology Report No. 19, the 1990 Integrated Assessment Report, and the 1992 Report to Congress, considered the delivery of wet and dry deposition to various types of material surfaces, particularly in urban areas.

4.4.1 Acidic Deposition Effects on Materials and Structures

Research conducted by NAPAP and other programs confirms that certain metals such as galvanized steel are corroded (Exhibit 65), surface coatings are degraded, and carbonate stone is dissolved by SO_2, wet-deposited acids, and natural atmospheric acidity from dissolved CO_2. Spotting of automotive finishes can also occur from acidic deposition.

To illustrate the potential role of acidic deposition, Exhibit 65 shows that an estimated 31 to 78 percent of the dissolution of galvanized steel and copper continues to be attributable to wet and dry acidic deposition. Acidic deposition can also accelerate deterioration of stone through three processes: dissolution and erosion of material or surface features; blackening of the stone surface; and cracking, splintering, and chipping of the stone surface. One of the most visible and documented forms of pollutant damage to limestone

[78] D.W. Dockery, C.A. Pope, X. Xu, J.D. Spengler, J.H. Ware, M.E. Fay, B.G. Ferris, and F.E. Speizer. 1993. An association between air pollution and mortality in six U.S. cities. *New England Journal of Medicine* 329:1753-1759.

[79] L.G. Chestnut and A. Patternson. 1994. *Human Health Effects Benefits Assessment of the Acid Rain Provisions of the 1990 Clean Air Act Amendments.* (Draft methodology report.) Prepared for the Acid Rain Division, U.S. Environmental Protection Agency, Washington, DC. (Currently being prepared for peer review.)

[80] This section is drawn primarily from the National Acid Precipitation Assessment Program, 1991 (*1990 Integrated Assessment Report.* NAPAP Office of the Director, Washington, DC.).

EXHIBIT 65. PERCENTAGE OF METAL CORROSION ATTRIBUTED TO ATMOSPHERIC FACTORS[a,b]

Metal Study Region	Corrosion Rate (μm/yr)	Dry Deposition of Sulfur	Acidity (hydrogen ion concentration)	Other Corrosion Factors
Galvanized Steel				
Adirondack Mtns, NY	0.62±0.26	6%	25%	69%
Washington, DC	1.01±0.42	52%	23%	25%
Steubenville, OH	1.47±0.21	56%	22%	22%
Copper				
Adirondack Mtns, NY	0.37±0.14	10%	25%	65%
Washington, DC	0.83±0.19	38%	25%	37%
Steubenville, OH	0.88±0.29	57%	20%	23%

[a] Source: NAPAP. 1993. 1992 Report to Congress. National Acid Precipitation Assessment Program, Washington, DC.

[b] Corrosion rates are mean measurements from NAPAP field sites.

and marble is the accumulation of dark gypsum (a mineral formed from calcium sulfate and water) crusts in areas sheltered from rain. Sulfur deposited onto carbonate stone (e.g., marble) reacts with calcite to form a black crust containing a mixture of gypsum, fly ash particles, soot, and biological growth, all of which can cause decay deeper into the stone. Laboratory and field studies show a correlation between dry deposition of SO_x and a thin black accumulation on masonry materials, including sandstone, granite, and brick. European studies show that SO_4^{2-} and NO_3^- concentrations in stone occur in proportion to atmospheric concentrations of SO_2 and NO_x. Erosion rates of stone in Europe, however, are significantly greater than those found in North America because of the higher ambient concentrations of acidic deposition precursors in Europe.

Rates of damage to materials associated with acidic deposition depend on atmospheric and structural factors that influence delivery of the pollutant to a material's surface, i.e., regulate its "dose." Wet deposition delivers atmospheric pollutants to surfaces of buildings, structures, and other objects primarily through rainfall, snowfall, fog, dew, and frost. Dry deposition provides a more constant delivery of pollutants as large particles fall with gravity and small particles and trace gases are delivered by atmospheric turbulence. Pollutants delivered by turbulent processes can potentially damage a greater proportion of material surfaces than can large particles. Also, a damp surface provides a much more effective sink for soluble trace gases (e.g., SO_2) than does the same surface when dry. Thus, dry deposition can often be intimately linked with the processes by which material surfaces are wetted.

The key effect of concern for cultural materials is physical damage, often expressed in terms of the time it takes for the material to lose its unique qualities. For construction materials, the key effect of concern is the expenditure to maintain an acceptable level of functionality and appearance over the life of the structure.

NAPAP studies reveal that U.S. regions with the largest number of cultural and historical monuments also often have the highest levels of acidic deposition, including areas of the Northeast having long settlement histories and the greatest number of pre-Civil War buildings and tombstones. Most historic battlefields, especially those with commemorative monuments, are located east of the Mississippi. Also, material selection has changed over time; more durable materials have replaced acid-sensitive marbles, sandstones, and zinc, which were predominantly used prior to large-scale western expansion and late 19th-century population increases. Distributions of acid-sensitive cultural materials are therefore expected to be less dense west of the Mississippi.

4.4.2 Material Life-Cycle and Damage Estimates

Potential acidic deposition-related damage to both function (e.g., building material, bridges, and automobile and other exterior coatings) and cultural value (e.g., historical monuments and sculp-

tures) potentially represent a very large overall cost to society. Acidic deposition control can therefore be linked to potentially large monetary benefits. Relating acidic deposition-induced physical damage to the shortened usefulness of materials remains an important area of research. Quantifying changes in maintenance and replacement cycles attributable to changes in acidic deposition is necessary for estimating the economic consequences of physical deterioration. The complexity of this linkage involves three primary areas:

- Extrapolation of laboratory findings to doses on large structures caused by ambient exposure;
- Tolerance to decay by acidic deposition, which varies with the specific function of the material within the structure; and
- Maintenance and replacement cycles, which can be affected by a great many factors other than acidic deposition, including market factors.

Clearly, emissions reductions can minimize the need for or frequency of public and private maintenance, repair, and replacement. EPA and NAPAP are working on approaches to estimate the damage to materials from acidic deposition. Assessing material effects present an array of options for valuing damages, costs, and benefits of emissions reductions in physical terms (e.g., corrosion rates and reduced service life), market terms (e.g., life-cycle costing and shifts in material selection and market share), and nonmarket terms (e.g., heritage valuation of damage to historical monuments and buildings). Several efforts have been initiated to determine the material damage costs associated with acidic deposition; damage to automotive coatings are highlighted here as one example of analyses. EPA and NAPAP have begun to investigate the costs of damage to automotive finishes and subsequent savings attributable to CAAA implementation.

Spotting of automotive finishes can occur from acidic deposition. This effect is most pronounced on dark finishes and in warmer climates, because the rate of chemical reactions causing spotting increases with temperature. The damage, typically appearing as irregularly shaped etched areas, occurs after evaporation of a moisture droplet. Automotive coatings may be damaged by all forms of acidic deposition, particularly when dry deposition is mixed with dew or rain. It has been difficult, however, to quantify the specific contribution of acidic deposition to paint finish damage relative to other forms of environmental fallout, the improper application of paint, or deficient paint formulations.

Although the existence of damage to automotive coatings has been well documented, there has been little analysis of the economic costs imposed by this damage. Such an analysis may include investigation of issues such as actions taken to prevent the negative effects of pollution (i.e., actions taken by car and truck manufacturers) and the market value of a car or truck damaged by acidic deposition (i.e., actions taken by automobile dealers regarding damage which has occurred). The scoping exercise conducted by EPA and NAPAP begins to illustrate the potentially large costs associated with this type of damage and therefore the significant benefits of the Acid Rain Program.[81] For example, estimates of annual costs to manufacturers of cars and trucks for including acid-resistant features can be as high as $400 million. Estimates of the value of potential annual residual damage to cars and trucks in the eastern United States may range from $50 million to over $400 million. Total annual costs could be $96 million to $850 million.

Additional materials damage and pollution reduction benefit efforts are also underway to determine the benefits of acidic deposition control on a functional item such as steel bridges as well as the potential benefits of control to preserve cultural resources of historical importance. Damage to cultural resources can result in potentially high repair and maintenance costs, replacement costs, and the value placed on one-of-a-kind resources. These and other costs associated with acidic deposition-induced damage would likely decrease with implementation of an acid deposition standard.

[81] ICF Incorporated. September 30, 1994. *Acid Rain Program Evaluation: Valuing Potential Reductions in Automobile Finish Damages–Scoping Study.*

CHAPTER 5

IMPLEMENTATION ISSUES

5.1 INTRODUCTION

In order to determine the effectiveness of an acid deposition standard for protecting sensitive resources, it is necessary to know not only the benefits that would result from a given standard if it were achieved, but also to know how the standard would be implemented.

In Section 404 of the CAAA, two requirements that Congress laid out for this acid deposition standard feasibility study dealt with implementation issues. The statutory language calls for:

- *Description of the measures that would need to be taken to integrate such standard or standards with the control program required by Title IV of the Clean Air Act; and*
- *Description of the impediments to implementation of such control program and the cost-effectiveness of deposition standards compared to other control strategies including ambient air quality standards, new source performance standards and the requirements of Title IV of the Clean Air Act.*

This chapter describes two basic approaches to implementing an acid deposition standard. Under the first approach, EPA would set a standard or standards, either using existing authority or seeking further authority from Congress to set such standards and provide deadlines for their attainment. Then, similar to Title I, states would determine source-specific limits using source-receptor models and cost analyses, incorporate those limits in state implementation plans (SIPs), and enforce them. If one or more states failed to do the above, EPA would promulgate a Federal implementation plan (FIP).

Under the second approach, Congress would direct EPA to set a deposition standard or standards and to determine the national (or regional) emissions levels for sulfur dioxide and nitrogen oxides that would meet those standards. Congress would then set an emissions cap and allowance allocations for nitrogen oxides and, if necessary, adjust the cap for sulfur dioxide in Title IV; and provide a timetable for meeting the new caps. EPA would use Title IV provisions to implement the emissions programs.

For these two basic approaches, this chapter will:

- Describe how each would be implemented, including any measures that would need to be taken to integrate it with Title IV;
- Describe any impediments to implementation, including the need for any additional statutory authority; and
- Discuss their relative cost-effectiveness.

To provide a rough comparison of the cost-effectiveness of the two approaches for sulfur reductions, estimates are made of the cost of achieving the same reduction in sulfur deposition at the three sensitive areas under each approach. The example used is based on a 50 percent reduction in national utility SO_2 emissions beyond that required by the 1990 CAAA (as described and modeled in Chapter 3). The use of this example in no way suggests that such a reduction is necessary, appropriate, or sufficient, but is merely put forth for illustrative purposes.

There are, of course, many variations on these basic approaches, and probably other ways to realize the goals of an acid deposition standard. The purpose here is not to provide a complete examination of this issue, but to show how existing approaches could be adapted to implement such a standard and to compare costs.

5.2 TARGETED APPROACH

5.2.1 Description of Targeted Approach

EPA would either set national standards for sulfur and nitrogen deposition, or set different regional standards for sulfur and nitrogen based on the different sensitivities of different regions to sulfur and nitrogen. (See 5.2.3 for a discussion of statutory authority.) EPA would also establish deadlines for the attainment of such standards, unless such deadlines were established through new statutory authority.

States would determine the form and level of emissions limits for the sources of sulfur and nitrogen that they determine relevant to the attainment of the national acid deposition standards. Their determinations would probably be based on atmospheric models and technical and cost analyses of the sources within their jurisdictions.

The process for making these determinations and incorporating such limits into SIPs would vary from state to state. Some states may wish to provide flexibility to their sources by allowing various forms of emissions trading. EPA would need to review each SIP and determine that it, in conjunction with other relevant SIPs, would attain and maintain the specific acid deposition standard or standards. States would be responsible for collecting emissions information and enforcing limits. If states failed to carry out these responsibilities, EPA would impose sanctions and/or prepare and implement a FIP. EPA would implement such a program through Titles I, II, and V. The program would be evaluated through deposition and effects monitoring.

5.2.2 Integration with Title IV

Setting an acid deposition or standards would not, by itself, directly affect other environmental programs unless it required emissions reductions. The specific sources and level of emissions reductions would determine the direct impact on other programs and usefulness of coordination and integration.

If no changes were made to Title IV, the allocation and transfer of allowances would not be restricted by state actions to set new emissions limits, but sources would not be able to emit more SO_2 than their state limits allow, regardless of how many allowances they might hold. This is the same situation as currently exists, but if more stringent limits were imposed on a large number of sources, the demand for and price of allowances would decline. In fact, taken to extreme if the aggregate effect of new source-specific state limits were to reduce utility SO_2 emissions below the current 8.95 million allowance cap and the SIPs did not allow emissions trading, the price of allowances should theoretically drop to zero because they would be of no use.

Both in setting the level of the standard and in its implementation, an acid deposition standard or standards should be coordinated and potentially integrated with several other environmental programs, particularly attainment and maintenance of primary and secondary National Ambient Air Quality Standards (NAAQS) for SO_2, NO_2, O_3, and PM_{10}; visibility protection; new source review; and new source performance standards under Title I of the CAAA. It would also be useful to coordinate acid deposition standard-setting and implementation with water quality programs, particularly involving eutrophication of estuaries. Substantial reductions in SO_2 or NO_x could assist in the achievement of the goals of these programs.

5.2.3 Impediments to Implementation

It may be possible to set acid deposition standards under existing statutory authority. At this time, no definitive determination has been made. However, clear direction from Congress in this area would certainly make implementation more feasible and effective. For example, implementation would be facilitated by explicit authority to set deposition standards, to set regionally different nitrogen and/or sulfur standards, to set deadlines for attainment, to require uniform measurement and reporting of emissions for sources not already affected by Title IV, and to establish uniform procedures for interstate trading of NO_x emissions. It would probably not be possible for sources to conduct efficient interstate trading of NO_x emissions without federal legislation.

Time and resource issues may be significant if, for example, a regionally targeted implementation approach shared some of the same administrative complexities as the current SIP process to meet the NAAQS. For instance, the development of state-specific regulations by states for emissions limitations, followed by EPA review and approval, can be a resource-intensive and lengthy process. EPA is currently working to streamline this process. Another concern is the incomplete and sometimes inconsistent state emissions inventory data upon which compliance and effectiveness is determined. Furthermore, if a state is not in attainment of the NAAQS, it is commonly a long period of time until state-specific air quality levels are achieved. Compliance deadlines for certain NAAQS have been refined and revised with each amendment to the CAA. The uncertainties of this process are not usually conducive to long-range planning and cost-effective compliance by the regulated community.

The 1990 CAAA recognized the role of long-range pollutant transport in ozone formation and authorized EPA to create "ozone transport regions" where nonattainment in one state may be the result of

emissions in another state. The newly created Northeast Ozone Transport Region extends from Northern Virginia to Maine. The Northeast Transport Commission is currently developing plans to achieve attainment of the ozone standard by determining both local and transport-region wide limits on nitrogen oxides emissions. The Commission is also considering market-based approaches (e.g., NO_x trading within the transport region) to achieve maximum protection at least cost. This effort represents a possible variation on the targeted regional approach.

Implementation of a targeted approach for determining and maintaining acid deposition standards would require, at a minimum, an enhancement of existing deposition monitoring and atmospheric modeling abilities. Program requirements would need to identify pollutants to be monitored, and determine standard procedures for measuring wet and dry deposition, spatial resolution, and temporal requirements. Enhanced effects monitoring (i.e., surface water monitoring) would be desirable to evaluate effectiveness of the standard or standards.

5.3 EMISSIONS-BASED APPROACH

5.3.1 Description of Emissions-Based Approach

Congress would direct EPA to provide (1) a range of target loads and emissions levels of sulfur and nitrogen designed to provide a range of ecosystem protection (and other benefits), (2) levels of national and regional sulfur and nitrogen emissions that met those target loads, and (3) estimates of the benefits and costs of meeting those emissions levels.

Taking this information into account, Congress would amend Title IV of the CAAA by setting an allowance cap for nitrogen, revising the cap for SO_2 (if necessary), including any new source categories (if necessary), allocating allowances, and providing timetables for the achievement of the new caps. EPA would implement through conforming changes to the Title IV rules. The program would be evaluated through deposition and effects monitoring.

5.3.2 Integration with Title IV

Depending on any statutory changes enacted, EPA would make conforming changes to the Title IV implementing regulations, 40 CFR Parts 72–78. Title IV permitting, allowance trading, emissions monitoring, penalty provisions and data systems would be used to ensure compliance. Since the information that EPA would provide Congress as input to their deliberations in setting allowance caps would include all human health and ecosystem impacts from sulfur and nitrogen known to EPA at the time, coordination with standard-setting and implementation of the other air and water programs cited above would be greatly facilitated. If the number of SO_2 allowance were lowered, allowance prices would rise. In certain cases, compliance strategies of affected sources may change.

5.3.3 Impediments to Implementation

New statutory authority would be needed. Title IV allowance levels for SO_2 cannot be changed without Congressional actions, and there is currently no allowance program for NO_x.

Administrative impediments would be limited to any difficulty posed by the statutory changes. Currently, Title IV does not appear to have any significant administrative or compliance impediments. Enhanced effects monitoring (i.e., surface water monitoring) would be desirable to track the effectiveness of deposition reductions.

5.4 ECONOMIC IMPACTS

If an acid deposition standard involves emissions reductions and requires stricter SO_2 and NO_x point source emissions controls, that standard would result in direct cost increases to utilities and industrial sources. The magnitude of cost increases, and the sectors most affected would vary depending on the regulatory approach selected, the quantity of emissions reduced, the sources affected, and the timing of the reductions. For the scenarios considered in this study, at least two comprehensive sector models—one for the electric utility industry and one for the industrial sector—would need to be applied to fully understand the wide ranging impacts that would result from an acid deposition standard. While such models exist, budget constraints did not allow for their use for this study. An expanded economic analysis would consider variations in emissions and the timing of achieving emissions reductions.

While the use of more precise sector models may become necessary if further emissions reductions are pursued, the scale of the economic analysis presented here is scoping in nature and limited in its degree of detail. Instead, this study uses:

- Analyses of the electric utility sector that have already been conducted by EPA to support Title IV.
- A spreadsheet-based scoping model to estimate broadly the range of costs associated with different regulatory approaches.

In Chapter 3, the impacts of various SO_2 control strategies on deposition in sensitive regions were evaluated for the year 2010. The costs of the key emissions control strategies described in Chapter 3 are evaluated below. Costs are estimated for the following control scenarios for the year 2010.

- 2010 CAAA Scenario,
- Additional 50 Percent Utility SO_2 Reduction Scenario,
- Additional 50 Percent Utility and Industrial SO_2 Reduction Scenario, and
- Geographically Targeted Utility SO_2 Reduction Scenarios.

The costs of additional utility and industrial NO_x reductions are described qualitatively. With the exception of the geographically targeted utility SO_2 reduction scenario, all cost scenarios are based on a national emissions-based approach.

5.4.1 2010 CAAA Scenario (With Trading)

The 2010 scenario with trading described in Chapter 3 is used as the baseline scenario for comparing costs of alternative emissions reductions scenarios. The costs of this scenario were developed as part of the 1993 EPA Base Case Analysis[82] used to support rulemaking under Title IV and have thus, been reviewed extensively. EPA has estimated that compliance with Title IV of the 1990 CAAA will cost electric utilities about 2.2 billion dollars in the year 2010 (Exhibit 66). SO_2 emissions forecasts project that SO_2 emissions decrease by about 9.2 million tons in 2010. This means that the average cost of reducing SO_2 is about $240 per ton SO_2 removed. The marginal SO_2 removal cost (i.e., the cost of reducing one additional ton of SO_2) is forecast to be much higher, however, about $500 per ton SO_2 removed.

With Title IV fully implemented, electric utility SO_2 emissions are forecast to equal about 9.5 million tons in 2010. This is higher than the 8.95 million ton SO_2 allowance cap that is binding in 2010 because:

It is forecast that about 0.52 million tons of allowances would be "banked" between 1995 and 2009 and used in 2010; and

Units not affected by Title IV (i.e., those with nameplate capacity less than 25 megawatts) would emit about 0.05 million tons of SO_2 in 2010.

Exhibit 66 shows utility costs and SO_2 emissions forecasts in 2010 by U.S. census region. As can be seen in the exhibit, the majority of SO_2 emissions reductions and compliance costs (about 60 percent of the U.S. total) are expected to occur in the central United States (i.e., East North Central and West South Central Census Regions).

5.4.2 50 Percent Utility SO_2 Reduction Scenario

For the 50 Percent Utility SO_2 Emissions Reduction Scenario, the 8.95 million ton electric utility SO_2 emissions cap was cut in half (i.e., set equal to 4.48 million tons SO_2). Under this scenario, costs are estimated to increase to $4.8 billion and SO_2 emissions are estimated to decrease by an additional 5 million tons in 2010 relative to the CAAA Scenario (Exhibit 67). The average cost of reducing SO_2 emissions by 5 million tons is about $955 per ton SO_2 removed, which is almost four times the average cost of emissions reductions forecast in the CAAA Scenario (i.e., $240 per ton SO_2 removed). The marginal cost of reduction is also much greater than in the CAAA scenario (i.e., about $1,225 per ton SO_2 removed versus $500 per ton SO_2 removed).

Costs and unit level SO_2 emissions for the 50 percent electric utility reduction scenario were forecast using EPA retrofit scrubber cost assumptions and unit level SO_2 emissions forecast in the CAAA Scenario. It was assumed that SO_2 emissions reduction would be achieved by unscrubbed coal-fired units not already forecast to use low sulfur coal in the CAAA scenario (i.e., unscrubbed units forecast to have an SO_2 emissions rate greater than 0.8 lbs SO_2 per million Btu). Using EPA scrubber cost assumptions used in the 1993 Base Case Analysis, costs were estimated for achieving the 5.0 million ton SO_2 emissions reduction.

[82] Economic Analysis of the Title IV Requirements of the 1990 Clean Air Act Amendments. 1994. U.S. EPA, Office of Air and Radiation, Acid Rain Division, February.

EXHIBIT 66: 2010 ANNUAL COSTS AND SO_2 EMISSIONS BY CENSUS REGION: CAAA SCENARIO

Census Region (States)	No Title IV	CAAA Scenario			
	Total SO_2 (Tons x 1,000)	SO_2 Removed (Tons x 1,000)	SO_2 Emissions (Tons x 1,000)	Annual Cost ($ Million)	Cost-Effectiveness ($/Ton SO_2 Rem. in 1994 dollars)
New England (CT,ME,MA,NH,RI,VT)	243	32	211	-17	-631
Middle Atlantic/Upper S. Atlantic (NY,NJ,PA,DE,MD,DC,VA,WV)	3,467	1,522	1,945	525	344
Lower S. Atlantic (FL,GA,NC,SC)	2,685	1,209	1,476	330	272
East N. Central (IL,IN,MI,OH,WI)	5,951	3,713	2,238	775	208
East S. Central (AL,KY,MS,TN)	2,885	1,728	1,157	500	287
West N. Central (IA,KS,MN,MO,NE,ND,SD)	1,826	839	987	185	219
West S. Central (AR,LA,OK,TX)	1,001	33	968	35	1,091
Mountain (AZ,CO,ID,MT,NV,NM,UT,WY)	500	33	467	-100	-3,061
Pacific (CA,OR,WA)	127	57	70	-25	-509
Total United States	**18,685**	**9,166**	**9,519**	**2,200**	**240**

EXHIBIT 67: 2010 ANNUAL COSTS AND SO_2 EMISSIONS BY CENSUS REGION: CAAA SCENARIO VERSUS ADDITIONAL 50 PERCENT UTILITY EMISSIONS REDUCTION SCENARIO

Census Region (States)	CAAA Scenario	Additional 50 Percent Electric Utility Emission Reduction Scenario			
	Total SO_2 (Tons x 1,000)	SO_2 Removed (Tons x 1,000)	SO_2 Emissions (Tons x 1,000)	Annual Cost ($ Million)	Cost-Effectiveness ($/Ton SO_2 Rem. in 1994 dollars)
New England (CT,ME,MA,NH,RI,VT)	211	132	79	125	955
Middle Atlantic/Upper S. Atlantic (NY,NJ,PA,DE,MD,DC,VA,WV)	1,945	1,107	838	1,060	955
Lower S. Atlantic (FL,GA,NC,SC)	1,476	836	640	800	955
East N. Central (IL,IN,MI,OH,WI)	2,238	1,269	969	1,200	955
East S. Central (AL,KY,MS,TN)	1,157	608	549	580	955
West N. Central (IA,KS,MN,MO,NE,ND,SD)	987	539	448	515	955
West S. Central (AR,LA,OK,TX)	968	428	540	410	955
Mountain (AZ,CO,ID,MT,NV,NM,UT,WY)	467	114	353	110	955
Pacific (CA,OR,WA)	70	14	56	13	955
Total United States	**9,519**	**5,047**	**4,472**	**4,800**	**955**

5.4.3 50 Percent Utility and Industrial SO_2 Reduction Scenario

Under this scenario, the 50 percent utility SO_2 emissions reduction is no different than described above. However, it is supplemented by a 50 percent reduction from industrial sources. As a result, costs are estimated assuming electric utility and industrial sources achieve a total reduction in SO_2 emissions of about 7 million tons in 2010 relative to the CAAA Scenario (Exhibit 68). Under the CAAA Scenario, utility and industrial sources are estimated to emit about 9.5 and 4.0 million tons of SO_2 in 2010 respectively. Commercial/institutional sources are expected to emit an additional 0.2 million tons. The cost of achieving the 50 percent electric utility and industrial source SO_2 emissions reduction is estimated to be about $6.5 billion annually. This corresponds to an average SO_2 emissions reduction cost of about $926 per ton SO_2 removed. As described in the previous section, the average cost of reductions for electric utilities is about $955 per ton SO_2 removed, and the average cost for industrial sources is estimated to be about $850 per ton SO_2 removed.

5.4.4 Geographically Targeted Reductions Scenario

Costs were calculated for both the contiguous and noncontiguous geographically targeted reduction scenarios corresponding to the deposition levels achieved by the 50 percent nationwide SO_2 utility reduction scenario for all three sensitive receptor regions and for all three regions together. These scenarios were constructed by sequentially removing 95 percent of utility SO_2 emissions (remaining after implementation of the Title IV) from subregions (either contiguously or in order of contribution to deposition) until the deposition loads were achieved. Ninety-five percent SO_2 emissions removal was necessary given the smaller number of sources from which to draw emissions. Costs were estimated by applying the EPA retrofit scrubbing cost assumptions to achieve 95 percent SO_2 removal from utility boilers identified in each subregion. Exhibit 69a provides costs for achieving the target deposition loads for each receptor region individually and for all three regions simultaneously for the contiguous approach. Exhibit 69b provides the same information for the non-contiguous case.

The total tons removed, about 4.6 million tons, the annual costs, about $4.6 billion, and the cost-effectiveness, about $1,000 per ton removed, are essentially identical for the contiguous and non-contiguous cases. Thus, no increase in efficiency would be gained by choosing the more complex non-contiguous approach over sequential contiguous geographical targeting.

Costs were not estimated for the geographically targeted utility and industrial scenario because specific cost functions for SO_2 removal from individual industrial sources were not available. Developing cost functions for individual industrial sources would require an extensive cost development effort beyond this scoping study.

5.4.5 NO_x Reductions—50 Percent Utility and Industrial

EPA is currently developing regulations for the control of NO_x emissions from electric utilities affected under Title IV of the CAAA. Regulations for Group I boilers in Phase I were promulgated on March 22, 1994.[83] Regulations for Group II boilers are under development and the costs and emissions reductions expected from these regulations were not available for this report. Preliminary information on the cost of controlling NO_x emissions from various types of electric utility boilers is available, however, from a recent EPA report.[84] These costs vary significantly depending on the type of technology applied, NO_x control efficiency, and boiler specific parameters. Some of the results presented in that report are described below.

Title IV of the CAAA requires EPA to set emissions limits for Group 1 boilers (i.e., dry bottom wall-fired and tangentially fired boilers) based on the application of low-NO_x burners (LNB) at affected electric utility units. In the RIA, which covers Group 1 boilers, EPA estimated that NO_x emissions would decrease by about 1.9 million tons annually and cost about $0.3 billion annually (an average cost of about $159 per ton NO_x removed).[85] The RIA considers a variety of NO_x con-

[83] See 59 *Fed. Reg.* 13538-80. On November 29, 1994, the U.S. Court of Appeals for the District of Columbia circuit vacated regulations and remanded them to EPA for further action. *Alabama Power Co. v. U.S. EPA*, No. 941170 (1994).

[84] *Alternative Control Techniques Document -- NO_X Emissions from Utility Boilers*, March 1994, U.S. EPA, Office of Air Quality Planning and Standards, EPA-453/R-94-023.

[85] *Regulatory Impact Analysis of NO_X Regulations*, February 1994, U.S. EPA Office of Atmospheric and Indoor Air Programs, Acid Rain Division.

EXHIBIT 68: 2010 ANNUAL COSTS AND SO_2 EMISSIONS BY CENSUS REGION: CAAA SCENARIO VERSUS ADDITIONAL 50 PERCENT UTILITY AND INDUSTRIAL EMISSIONS REDUCTION SCENARIO

Census Region (States)	CAAA Scenario*	Additional 50 Percent Utility and Industrial Reduction Scenario			
	Total SO_2 (Tons x 1,000)	SO_2 Removed (Tons x 1,000)	SO_2 Emissions (Tons x 1,000)	Annual Cost ($ Million)	Cost-Effectiveness ($/Ton SO_2 Rem. in 1994 dollars)
New England (CT,ME,MA,NH,RI,VT)	328	182	145	175	955
Middle Atlantic/Upper S. Atlantic (NY,NJ,PA,DE,MD,DC,VA,WV)	2,719	1,456	1,263	1,360	930
Lower S. Atlantic (FL,GA,NC,SC)	1,919	1,052	867	980	934
East N. Central (IL,IN,MI,OH,WI)	3,458	1,857	1,601	1,740	937
East S. Central (AL,KY,MS,TN)	1,653	842	811	780	930
West N. Central (IA,KS,MN,MO,NE,ND,SD)	1,402	727	674	670	921
West S. Central (AR,LA,OK,TX)	1,699	803	896	700	869
Mountain** (AZ,CO,ID,MT,NV,NM,UT,WY)	467	114	353	110	956
Pacific** (CA,OR,WA)	70	14	56	13	929
Total United States**	**13,714**	**7,047**	**6,667**	**6,500**	**926**

* Total includes 9,519 thousand tons utility emissions and 4,195 thousand tons industrial emissions.
** Totals do not include industrial SO_2 emissions from the Mountain and Pacific Regions.

EXHIBIT 69A: ANNUAL COSTS OF GEOGRAPHICALLY TARGETED REDUCTIONS EQUIVALENT TO NATIONWIDE 50% UTILITY SO_2 REDUCTION (CONTIGUOUS RADM SUBREGIONS)

	Sensitive Region			All Three Receptor Regions
	Adirondacks	Mid-Appalachians	Southern Blue Ridge	
Emissions Reduction (tons)	3,018,000	1,952,000	1,508,000	4,526,000
Cost ($ million)	3,131	2,127	1,610	4,741
Cost-Effectiveness ($/ton)	1,037	1,089	1,068	1,048

EXHIBIT 69B: ANNUAL COSTS OF GEOGRAPHICALLY TARGETED REDUCTIONS EQUIVALENT TO NATIONWIDE 50% UTILITY SO_2 REDUCTION: MAJOR RADM SUBREGIONS CONTRIBUTING TO DEPOSITION (NOT CONTIGUOUS)

	Sensitive Region			All Three Receptor Regions
	Adirondacks	Mid-Appalachians	Southern Blue Ridge	
Emissions Reduction (tons)	3,160,000	2,079,000	2,081,000	4,658,000
Cost ($ million)	3,151	2,193	1,952	4,523
Cost-Effectiveness ($/ton)	997	1,054	938	971

trol technologies.[86] Applied to pre-New Source Performance Standard (NSPS) coal-fired electric utility boilers, these technologies are capable of achieving NO_x emissions reductions of about 10 to 60 percent. On a boiler operating in baseload, these technologies are estimated to cost from about $100 to $1,000 per ton NO_x removed.

To reduce electric utility NO_x emissions by more than required by Title IV, it would be necessary to apply technologies with NO_x removal efficiencies and costs greater than LNB technology. It would be necessary for sources would be required to apply selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) technologies. SCRs can achieve NO_x removal efficiencies ranging from 75 to 85 percent. In combination with LNB technologies, SCRs can reach removal efficiencies of 85 to 95 percent. EPA estimates that a stand alone SCR would cost from $810 to $2,490 per ton NO_x removed at a coal-fired unit operating in baseload. In combination with LNB technology, SCR application could cost about $1,300 to $2,490 per ton NO_x removed. These cost would be expected to decline with the wide-scale application of SCR throughout the electric utility industry, based on economies of scale.

As with utility boilers, a wide variety of NO_x control technologies are applicable to industrial boilers. These include LNB technologies, SNCR, and SCR. It is usually more cost-effective to apply these technologies to electric utility boilers than to industrial boilers because electric utility boilers generally provide more suitable operating conditions and economies of scale.

5.4.6 Summary of Economic Impacts

Exhibit 70 summarizes the total costs and costs per ton of SO_2 removed for each reduction strategy for which costs were developed. The additional 50 percent nationwide SO_2 utility reduction scenario is a factor of four less cost-effective than the CAAA baseline. This is not surprising since the allowance trading program was designed to achieve maximum cost- effectiveness, and, thus, utility reductions beyond that required by the Act would necessarily be less economically attractive. Additional emissions reductions would likely impact the emissions trading program and limit the compliance flexibility inherent in the current program. From Exhibit 70 it is apparent that difference in

[86] The Court held in *Alabama Power Co. v. U.S. EPA* that EPA's definition of low-NOx burner in the March 22, 1994, regulations was too broad. That ruling does not affect the use of information developed for the RIA in this scoping economic analysis.

EXHIBIT 70. SUMMARY OF COSTS OF VARIOUS EMISSIONS REDUCTIONS SCENARIOS

Scenario	SO_2 Removed (Tons x 1000)	Annual Cost ($ Billion)	Cost-Effectiveness ($/Ton SO_2 Rem. in 1994 dollars)
CAAA baseline	9,166	2.2	240
50% utility SO_2 removal	5,047	4.8	955
Targeted utility SO_2 removal (contiguous)	4,526	4.7	1,048
Targeted utility SO_2 removal (not contiguous)	4,658	4.5	971
50% utility and industry SO_2 removal	7,047	6.5	926

costs between the nationwide and geographically targeted SO_2 emissions reductions strategies to achieve the same level of deposition are not significant. Therefore, there does not appear to be a significant cost advantage to adopting a geographically targeted approach to achieving the deposition levels attained by the nationwide 50 percent SO_2 utility reduction scenario. Interestingly, the 50 percent utility and industrial reduction scenario is about equal in cost-effectiveness to the 50 percent utility reduction scenario. This indicates that emissions reductions from major industrial sources would be as cost-effective as additional utility reductions.

The costs presented in this economic analysis were based on conventional SO_2 scrubbing and are scoping in nature. These costs should be viewed as conservative (i.e., over-stated) in that within the time frame in which acid deposition standards could be developed, newer innovative technologies may become available which may be less costly than conventional scrubbing, including clean coal technologies, repowering with natural gas, or increased use of pollution prevention technologies such as renewal energy and conservation.

If further emissions reductions were mandated by Congress in order to implement an acid deposition standard, there may be a greater impetus for the commercial deployment of clean coal technologies in the U.S. market place as well as other repowering or pollution prevention technologies.

5.5 CONCLUSIONS

In this chapter, the discussion has been focused on implementation issues associated with an acid deposition standard. Assuming that a decision were made to reduce emissions of sulfur dioxide and/or nitrogen oxides beyond the current Clean Air Act to address the acidification of surface waters and/or the multiple effects associated these pollutants, it is feasible to implement such an approach. There are different approaches that could be taken and various factors to be considered (administrative complexity, resource demands on the government and regulated industry, costs, interactions with other programs). Based on the multiple effects of acidic deposition and its sulfur and nitrogen precursors, it is recommended that if further emissions reductions are pursued, they be as broad as possible; either a national approach or a regional approach that incorporated a large area of the country (e.g., east of the Mississippi River). Furthermore, Title IV is an administratively efficient way to achieve emissions reductions with the basic infrastructure already set up under Title IV being well-suited to incorporate further sulfur dioxide and nitrogen oxides emissions reductions. The costs of further emissions reductions characterized in this report could lead to costs that are more than double those of the current acid rain control program, but the timing of those reductions would affect the costs and the benefits. The benefits would likely be in multiple effects areas. Compliance costs could be significantly impacted by the timing of any further emissions reductions. Any additional reductions which may be required later rather than earlier may cost less based on cost-saving technologies demonstrated through clean coal technology and pollution prevention efforts and based on the replacement of existing sources by new, lower emitting sources.

CHAPTER 6

INTEGRATION AND CONCLUSIONS

6.1 INTRODUCTION

Section 404 Appendix B of the Clean Air Act directs EPA to assess the feasibility and environmental effectiveness of an acid deposition standard or standards to protect sensitive ecosystems. This chapter summarizes and integrates the findings from the previous chapters showing how scenarios for potentially reducing acidic deposition described in Chapter 3 address environmental goals defined in Chapter 2. Chapter 4 described potential benefits to visibility, human health, material, and cultural resources accompanying additional reduc-tions in acidic deposition. Chapter 5 addressed feasibility and effectiveness of implementing a deposition standard.

Section 6.2 highlights the conclusions that are key to establishing effective environmental goals and efficient deposition control strategies. Section 6.3 then integrates these findings to show the potential surface water benefits from a selection of alternative emissions reduction scenarios, considering a range of times to watershed nitrogen saturation.

6.2 ESTABLISHING EFFECTIVE ENVIRONMENTAL GOALS

Defining appropriate environmental goals and projecting future effectiveness of various control options requires characterizing potential environmental effects and benefits over a range of sulfur and nitrogen deposition loadings. A regionally specific approach to determining a deposition standard or standards can provide the basis for implementation under either regional or national approach. Resource-specific goals can be used to determine what emissions and deposition reductions would likely be needed. A regionally specific environmental goal (i.e., acid deposition standard) can be used to achieve effective and efficient environmental protection of those resources and ecosystems most sensitive to adverse effects and most likely to benefit from acidic deposition control.

Establishing appropriate environmental goals for an acid deposition standard or standards requires selection of appropriate ecological endpoint criteria and indicator measures. Such measures must provide information to accurately judge how successfully the key ecosystems and resources of concern are being protected. The applicability of these measures varies among regions and, in some cases, among individual systems (e.g., watersheds, lakes, or streams). While the analysis presented in this chapter focuses on changes in surface water quality reflected by two ANC measures within these waters, other endpoints may be equally or more appropriate for protecting sensitive resources of local interest, such as individual stands of red spruce forests or populations of listed threatened or endangered species. Potentially useful endpoints can include the "most sensitive" systems or species within an environment or some defined index of ecological structure.

Several major points and conclusions from the research and analyses presented in the previous chapters are key to the process of integrating our understanding of environmental effects and source-receptor relationships related to acidic deposition and setting effective environmental goals. The following points highlight the processes and relationships described earlier in this report.

- CHEMICAL EMISSIONS AND ATMOSPHERIC PROCESSES AFFECTING DEPOSITION ACIDITY: The principal acids in deposition are sulfuric (H_2SO_4) and nitric (HNO_3) acids. Thus, emissions of compounds containing sulfur and nitrogen have been the primary focus in acidic deposition control strategies. Volatile organic compounds (VOCs) and their oxidation products are also important because they often control reactions that produce the oxidizing species that lead to formation of sulfuric and nitric acids in the atmosphere. In total, production of atmospheric acids is a complex process, involving 140 known reactions among 60 chemical species, 40 of which are organic compounds.
- NATURAL EMISSIONS SOURCES: Natural emissions of acid precursor species, organic matter, and alkaline materials (dust) are

generated by vegetative matter, soil and saltwater microbes, geochemical activity, lightning, and natural combustion (e.g., forest fires). Natural emissions of SO_2, sulfates, and nitrogen oxides are significantly less important than anthropogenic sources in their impact on sensitive ecological resources.

- ANTHROPOGENIC EMISSIONS SOURCES: Acidic deposition precursor species and reactive atmospheric chemicals are generated by energy production, industrial processes, mobile sources, and waste disposal. Current estimates indicate that of the total emissions of SO_2, electric utility fuel combustion contributes 70 percent, industrial fuel combustion contribute 14 percent, and the balance comes from other sources. For emissions of NO_x, both electric utility fuel combustion and highway vehicles each are estimated to contribute 32 percent, industrial fuel combustion provides 15 percent, and off-highway vehicles produce 12 percent, with the balance coming from other sources. Potential future needs to effectively and efficiently further reduce anthropogenic source emissions and deposition would likely focus primarily on limiting emissions from these major sources.

- CHEMICAL CAUSES OF ACIDIC DEPOSITION EFFECTS: Accumulating scientific evidence verifies that deposition of acid-forming sulfur and nitrogen compounds both can be significant causes of surface water acidification effects. Although past research and control efforts have primarily focused on the control of sulfur emissions and deposition, recent research indicates that nitrogen deposition often may be an equally and sometimes more important cause of some surface water acidification effects. For example, considerable evidence indicates that nitrogen deposition is generally a greater acidification concern in the western United States and that nitrogen deposition as well as sulfur deposition can be a significant contributor to episodic acidification of surface waters in the East.

- WATERSHED NITROGEN SATURATION: There are limits to the amount of nitrogen that can be sequestered (i.e., in organic matter) in watersheds. As these systems approach saturation, nitrogen losses from watersheds will increase leaching of nitrate. This can lead to acidification of surface waters. Times to nitrogen saturation vary among regions due to differences in temperature, moisture, length of growing season, soil fertility, forest age, history of nitrogen deposition, and other variables. Significant variability and uncertainties remain in determining the time to nitrogen saturation for specific watersheds across regions. Nitrogen saturation is a potentially significant concern that contributes to the acidification process, even if total saturation never occurs.

- MOST SENSITIVE REGIONS AT RISK: Based on the NAPAP National Surface Water Survey, six regions contain 95 percent of the lakes and 84 percent of the stream reaches that were chronically acidified [i.e., having an acid neutralization capacity (ANC) of 0 μeq/l or less] due to inorganic ions, predominantly SO_4^{2-}, NO_3^-, and Cl^-. These areas include the southwest Adirondack Mountains in New York, New England, mid-Appalachian Region, Atlantic Coastal Plain, northern Florida Highlands, and low-silica lakes in the upper Midwest. Compiled evidence indicates that acidic deposition most likely caused significant acidification of surface waters in the Adirondacks, the Pocono/Catskill subregion, mid-Appalachians, eastern upper Midwest, the New Jersey Pine Barrens, and, to a lesser extent, northeastern Florida. These regions, therefore, require greatest consideration when determining the need for protection from future acidic deposition loadings.

- MOST SENSITIVE RESOURCES AT RISK: An acid deposition standard or standards intended to prevent adverse effects should provide adequate protection for the most sensitive resources at greatest risk. The predominant natural resources that appear to be both most sensitive to and at greatest potential risk from acidic deposition are aquatic systems and high-elevation red spruce forests.

- NATURALLY ACIDIC SURFACE WATERS: Evaluation of acidic deposition should include the realization that all regions hold naturally acidic surface waters. For example, about 40 to 50 percent of the target population surface waters in the Adirondacks with ANC of 50 μeq/l or less (i.e.,

sensitive) are likely to persist even with complete elimination of anthropogenic acidic deposition. Certain biota evolve to live in naturally acidic systems. Management and policy decisions should recognize the existence of these systems and consider protecting populations and communities that have naturally evolved as part of these ecosystems.

- ENVIRONMENTAL GOALS TO PROTECT SENSITIVE AQUATIC RESOURCES: The biological effects of inorganic monomeric aluminum associated with acidic deposition are minimized as the level of acidic deposition is decreased and pH and ANC levels in sensitive waters are kept relatively high. Based on laboratory and field studies of sensitive aquatic species, a general goal is to maintain surface water pH above 6.0. Greatest protection of sensitive aquatic resources occurs in surface waters where ANC is generally maintained above 50 μeq/l.
- EPISODIC ACIDIFICATION: Short term acute effects occur when pulses of acidic waters enter lakes or streams with storm runoff and snowmelt. The resulting potentially acutely toxic changes in surface water chemistry often occur at the most biologically significant time of year. The projected number of systems at risk of episodic acidification is substantially higher than the number of chronically acidic systems.
- CRITICAL AND TARGET LOADS: A critical load is a quantitative pollutant loading below which no significant harmful effects occur to ecological processes; a critical load depends solely on inherent ecological properties. A target load may incorporate social, policy, economic, and other considerations along with the scientific observations. Protection approaches emphasizing critical and target loads are currently used extensively in most European countries and Canada. A critical and/or target load approach is conceptually similar to the deposition standard approach discussed in this report for determining the most appropriate level of protection.

  This report does not develop or set critical or target loads. It does, however, provide the scientific basis upon which to determine critical loads. The scientific uncertainty regarding watershed nitrogen saturation makes determining a standard difficult at this time.
- MONITORING TO ASSESS EFFECTIVENESS AND BENEFITS OF CONTROLS: Although the analyses presented in this report focused on environmental goals appropriate for reducing regional proportions of surface waters with ANC below 0 μeq/l and maintaining surface water ANC above 50 μeq/l, monitoring to assess the actual effectiveness of any emissions or deposition controls should assess not only the potential benefits of controls on surface water ANC, but also on other resources of concern. Such concerns include possible changes in the stand condition within red spruce forests at potential risk, visibility impairment particularly in National Parks, and degradation of materials and cultural resources.
- REGIONALLY BASED RESEARCH: Outside the context of an acid deposition standard, regionally based ecological knowledge can be used to help guide efforts to improve or monitor the ecological health of sensitive areas.

6.3 PROJECTED ENVIRONMENTAL CONSEQUENCES OF ACIDIC DEPOSITION REDUCTION SCENARIOS

From the above summary of findings, the surface waters in the United States at greatest apparent continuing risk from acidic deposition extend from the Adirondacks south along the Appalachian chain into northern Florida. Past research has primarily focused on understanding acidic deposition relationships within three representative case-study regions along this area, particularly lakes in New York's Adirondack Mountains, acid sensitive stream reaches in the mid-Appalachian Region (portions of New York, New Jersey, Pennsylvania, Maryland, West Virginia, and Virginia) and Southern Blue Ridge Province (portions of North Carolina, South Carolina, Tennessee, and Georgia). These representative regions receive fairly high levels of acidic deposition, have the best historical data and are best understood by scientists.

Potential benefits of additional sulfur and nitrogen deposition reductions to the three sensitive aquatic resource regions were projected using relationships defined through the Nitrogen Bounding Study (NBS) discussed in Chapter 2 and shown in Appendix B. Specifically, the scenarios presented

in Exhibits 40 and 49 in Chapter 3 that provide for the maximum reduction in acidic deposition levels by the year 2010 represent approximately a 44 percent decrease in SO_2 emissions from all sources and a 24 percent decrease in projected NO_x emissions beyond those achieved by the 1990 CAAA. These deposition reductions were produced by reducing both sulfur and nitrogen emissions from utility and industrial combustion sources by 50 percent. The NBS projections were then used to relate the resulting sulfur and nitrogen deposition levels to probable proportions of surface waters in the two ANC groupings. Because times to watershed nitrogen saturation are not certain for these three or any other region, projections using all four possible times for watersheds to reach nitrogen saturation modeled by NBS were prepared.

Exhibits 71–73 present actual and modeled proportions of lakes and streams for two ANC groupings (ANC≤0 μeq/l and ANC≤50 μeq/l). Projected proportions in both of these ANC categories are shown for each of the three study regions under each of four possible times to watershed nitrogen saturation for the following six scenarios:

- Actual 1984 or 1985,
- NBS projections of surface waters in the year 2040 if the 1990 CAAA had not been implemented,
- NBS projections of surface waters in the year 2040 with full implementation of the 1990 CAAA.
- NBS projections of surface waters in the year 2040 with additional reductions in utility and industrial emissions of sulfur beyond the CAAA (see Exhibit 40).
- NBS projections of surface waters in the year 2040 with additional reductions in utility and industrial emissions of nitrogen beyond the CAAA (see Exhibit 48).
- NBS projections of surface waters in the year 2040 with additional reductions in utility and industrial emissions of both sulfur and nitrogen beyond the CAAA (see Exhibits 40 and 49).

EXHIBIT 71. YEAR 2040 NBS PROJECTIONS FOR ADIRONDACK LAKES

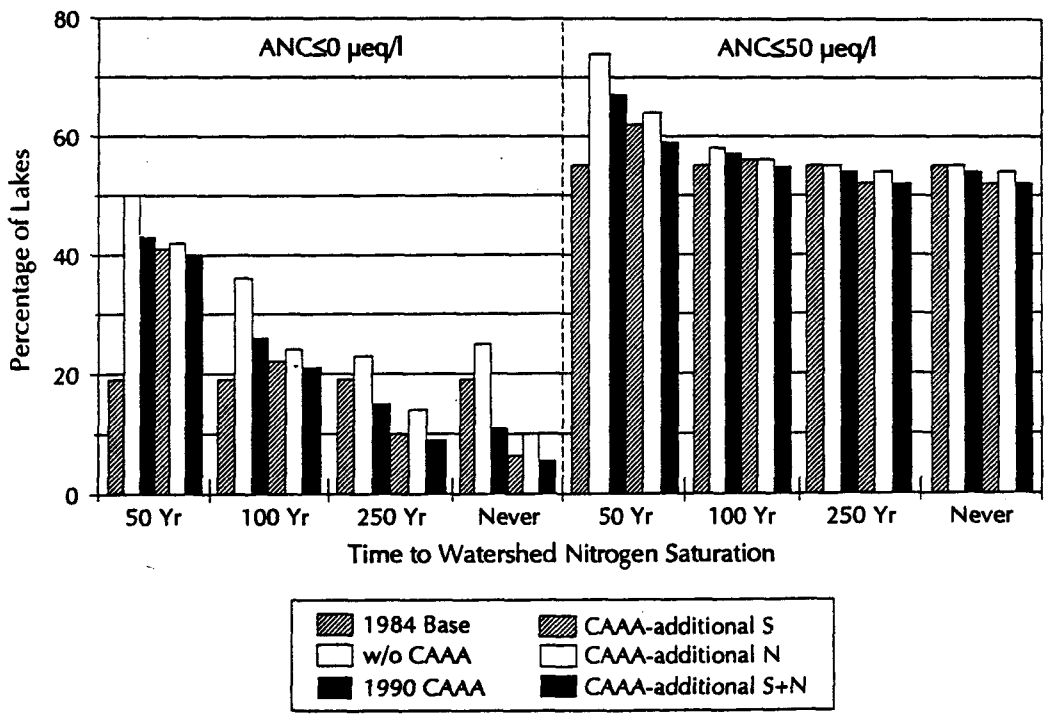


EXHIBIT 72. YEAR 2040 NBS PROJECTIONS FOR MID-APPALACHIAN STREAMS

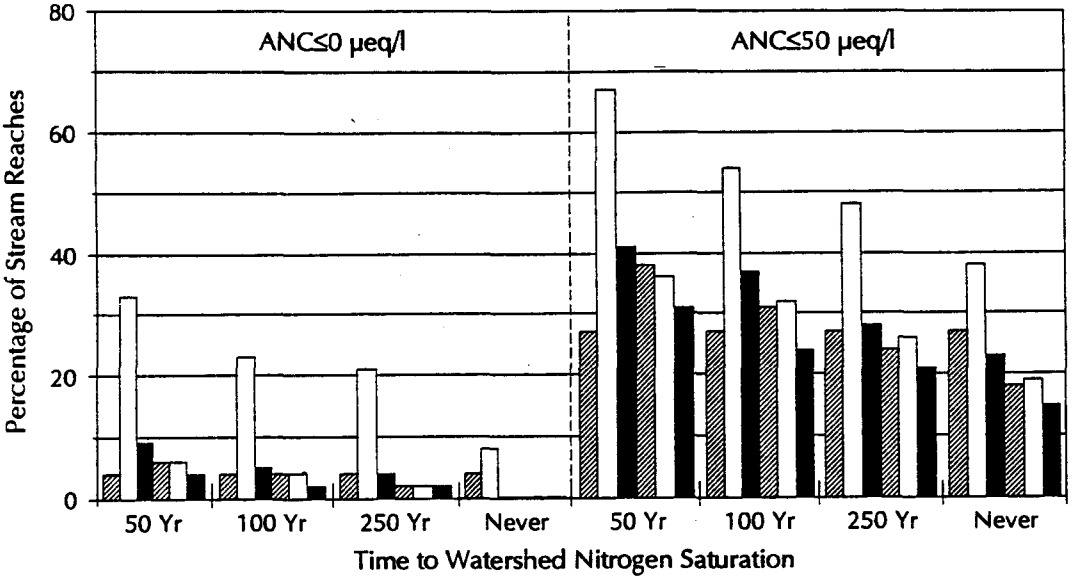
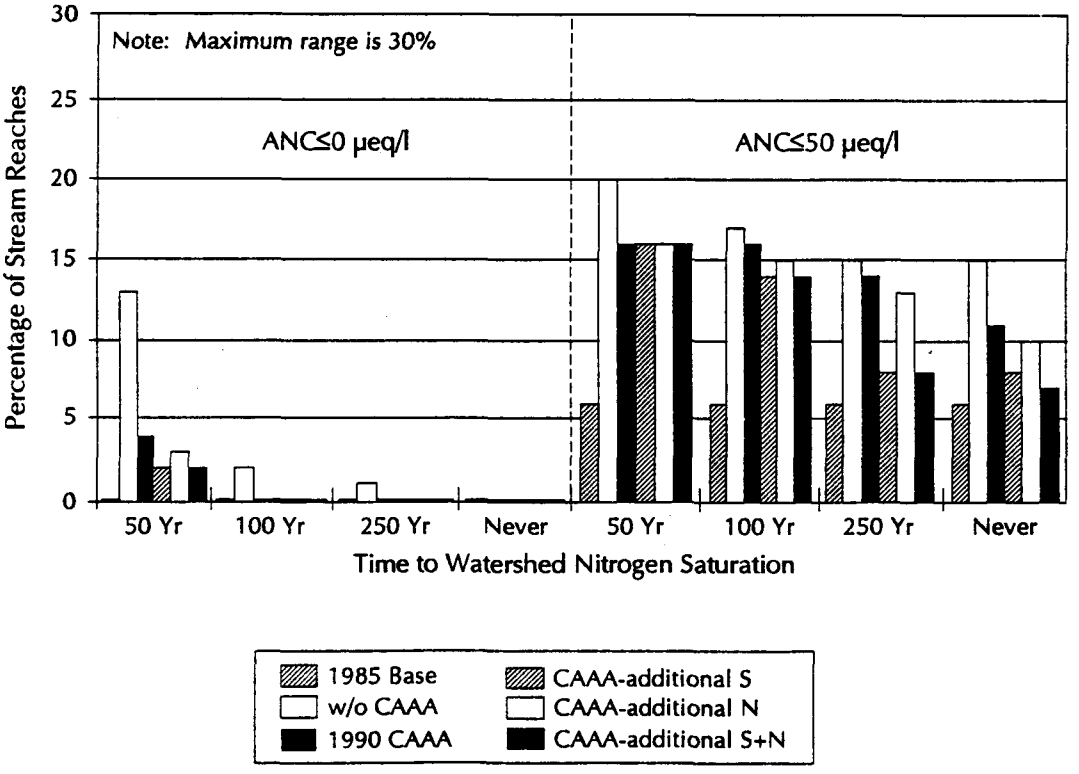


EXHIBIT 73. YEAR 2040 NBS PROJECTIONS FOR SOUTHERN BLUE RIDGE PROVINCE STREAMS



The following points highlight the major relationships shown in the projections for the year 2040. In reviewing these projections, it is important to remember that these projections are for changes in proportions representing the NBS modeled subpopulations of the "most sensitive surface waters" within each of these regions; these proportions do not apply to all the surface waters or some other subset of surface waters in these regions.

- The 1990 CAAA markedly reduces the proportions of surface waters in all three regions projected to be acidic (i.e., ANC≤0 μeq/l) by 2040, relative to conditions projected without its implementation. This is seen by comparing the second and third vertical plotted bars shown for each region and across each assessed time to watershed nitrogen saturation.
- The 1990 CAAA markedly reduces the proportions of stream reaches in the mid-Appalachians projected to become increasingly sensitive to potential effects from episodic acidification (i.e., ANC≤50 μeq/l) by 2040. This benefit is projected to be lesser in magnitude for the lakes in the Adirondacks and stream reaches in the Southern Blue Ridge.
- Sensitivities of target aquatic resources and their potential responses to changes in acidic deposition clearly differ among the modeled regions.
- The benefits to sensitive surface waters from sulfur deposition reductions mandated by the 1990 CAAA may be lessened due to future increases in nitrogen leaching caused by continuing nitrogen deposition and saturation of watersheds with deposited nitrogen. This is shown by the projected increasing proportion of ANC≤0 μeq/l and ANC≤50 μeq/l surface waters at shorter times to watershed nitrogen saturation.
- Uncertainty related to actual times to watershed nitrogen saturation within these regions causes projections of relationships between deposition and ANC responses to range by factors of about two or greater. Longer times to nitrogen saturation lead to fewer projected acidic and sensitive aquatic systems.
- Significant uncertainty continues to accompany the rate of watershed nitrogen saturation, contributing to uncertainty in projecting the impact of additional reductions in sulfur and nitrogen deposition.
- Any reductions in nitrogen deposition would not only reduce total acidic deposition, but would also increase the actual times to watershed nitrogen saturation. This is similar to sulfur deposition reductions that are now likely extending times for watershed sulfur saturation.

6.4 FEASIBILITY OF ESTABLISHING AND IMPLEMENTING AN ACID DEPOSITION STANDARD

A variety of factors could affect the implementation of an acid deposition standard. The effect of these factors on implementation will depend on the approach selected. To be successful, an implementation approach must be clear and unambiguous, and provide certainty as to the responsibilities of the regulated community, EPA, and states. Two basic approaches were evaluated in this report. First, a regional targeted approach would involve establishing deposition standards for specific geographic regions, and require geographically targeted reductions in emissions of SO_2 and/or NO_x. EPA would either set a standard or standards using existing authority or would seek additional congressional authority and timetables. Source-specific limits would be determined using source-receptor models, and limits would be incorporated into State Implementation Plans (SIPs) and enforced by states. Second, a national, emissions-based approach which would involve congressional direction to EPA to set an acid deposition standard or standards and determine emissions for SO_2 and NO_x to meet the standards within a certain time frame. An emissions cap and allowance allocations would have to be set for NO_x and, as appropriate, adjusted for SO_2. The regional approach would be similar to the SIP program used to implement Title I of the Act regarding attainment of National Ambient Air Quality Standards (NAAQS) while the national approach is similar to the current Acid Rain Program.

Two emissions reductions scenarios were developed to compare national and targeted reductions—a nationwide 50 percent reduction beyond the CAAA of SO_2 emissions from utilities and a geographically targeted strategy which removed 95 percent of utility SO_2 emissions from geographically constrained regions. Both approaches

were analyzed for emissions reduction efficiency and cost-effectiveness. The following points highlight the findings and conclusions from these analyses.

- Geographic targeting can be used to achieve target loads in each receptor region and in all three regions simultaneously. Delineation of targeted emissions reduction areas is made complex, however, by potentially large target areas, significant source-specific emissions reductions requirements (i.e., 95 percent SO_2 reductions), and impairment to the cost savings of the current Acid Rain Program due to regional restrictions on allowance trading.
- The total emissions reductions required to achieve the deposition loads in all three receptor regions simultaneously did not differ significantly between the nationwide and targeted approaches. Costs of control and cost-effectiveness for the nationwide emissions reduction scenario and the geographically targeted scenario were approximately equal. (To assess the approaches, each scenario was designed to achieve the same environmental goal.) There is no environmental or economic gain by geographically targeting source regions.
- Title IV will produce the largest emissions reductions in the highest source regions (i.e., Ohio, Indiana, West Virginia, and western Pennsylvania) making control efforts beyond the CAAA more effective if focused on broad geographic regions, or nationally.
- The cost of additional emissions reductions addressed in this report are, at a minimum, double the cost of the current Acid Rain Program. The benefits, although not quantified here, would be in multiple effects areas such as human health, visibility, and materials, as well as aquatic systems.

Based on scientific understanding of the effects of sulfur and nitrogen, it would be feasible to set sulfur and nitrogen deposition standards to protect aquatic resources. However, uncertainty regarding the impact of nitrogen remains high, making it difficult to determine the appropriate level of a standard or standards at this time.

APPENDIX A

SUMMARY OF SELECTED NAPAP REPORTS

APPENDIX A

SUMMARY OF SELECTED NAPAP REPORTS

INTRODUCTION

This appendix presents a synopsis of major conclusions from 10 of the NAPAP State of Science and Technology Reviews. In a few of these summaries, where knowing how the study was designed and conducted can help the reader better appreciate the study's key results, background information on the study's methods is presented. Most information summarized in this appendix came from NAPAP's *Summary Report of the U.S. National Acid Precipitation Assessment Program.*[1] Major conclusions from these NAPAP studies that influence identifying key relationships between acidic deposition and receptor effects are presented in the order that they were presented by the individual SOS/T report summaries. Also, not all conclusions from those studies are presented in the following sections. In some case, similar key conclusions appear in more than one report, consequently, they are also repeated in more than one of the case summaries below.

SOS/T REPORT 9: CURRENT STATUS OF SURFACE WATER ACID-BASE CHEMISTRY

Phase I of the National Surface Water Survey (NSWS) consisted of three major surveys. The 1984 Eastern Lake Survey (ELS) sampled 1,592 lake of 4 ha and larger that represented an estimated population of 17,953 lakes in the Northeast, Upper Midwest, the Southern Blue Ridge region, and Florida. The 1985 Western Lake Survey (WLS) sampled 719 lakes of 1 ha and larger that represented an estimated population of 10,393 lake throughout the Sierra Nevada, Cascade, and Rocky Mountain ranges. Finally, the National Stream Survey (NSS) sampled 500 stream reaches in 1986 that represented an estimated population of 56,000 stream reaches (200,000 km) throughout much of the Mid-Atlantic Coastal Plain, mid-Appalachian, Poconos/Catskills, Interior Southeast, and Florida Regions. A Phase II lake survey (ELS-II) was conducted in 1986 to evaluate seasonal chemical variability in Northeast Lakes. Thus, seven major subregions were sampled during the NSWS:

- Northeast Subregion
- Mid-Appalachian Subregion
- Mid-Atlantic Coastal Plain Subregion
- Interior Southeast Subregion
- Florida Subregion
- Upper Midwest Subregion (northern Michigan, Wisconsin, and Minnesota)
- West Subregion

Several key findings from the NSWS include:

1. An estimated 4.2% (1,181) of the National Surface Water Survey (NSWS) lakes were acidic, *defined as having ANC≤0 μeq/l;* nearly all were in the East. These lakes had pH levels in the range 5.0 to 5.5.
2. Acid lakes tend to be smaller than non-acidic lakes. In the East acidic lakes average 12 ha versus 17 ha for non-acidic lakes.
3. Nearly 20% of the NSWS lakes had an ANC of 50 μeq/l or less.
4. About 3.0% of the NSWS lakes had total inorganic monomeric aluminum (Al_{im}) concentrations of less than 50 μg/l.
5. No sampled lakes were acidic in the Interior Southeast or Minnesota, and only one, a geothermal spring, was acidic in the West. These results lead to the conclusion that there are virtually no acidic lakes in these subregions, within the subpopulation of surface waters sampled.
6. Based on total stream length with the NSS target population, 2.7% (5,506 km) were acidic (ANC≤0 μeq/l) and 12% (23,595 km) had ANC≤50 μeq/l, excluding reaches affected by acid mine drainage.

[1] Irving, P.M. 1991. *Acidic Deposition: State of Science and Technology.* Summary Report of the National Acid Precipitation Assessment Program. Office of the Director, National Acid Precipitation Assessment Program, Washington, DC.

7. For 8% (16,780 km) of the NSS stream length, the pH was 5.5 of less and for 18% (35,771 km) the pH was 6.0 or less.

8. A greater percentage of streams reaches were acidic in their upstream reaches (6.1%) compared to their downstream reaches (2.3%)

9. Most of the acidic stream reaches in the NSWS target population occurred in the mid-Appalachian and Mid-Atlantic Coastal Plain regions, with smaller length totals in the Poconos/Catskill subregion and Florida.

10. Acidic and low pH streams in the mid-Appalachian region and Poconos/Catskill subregions were restricted to watersheds smaller than 30 km^2 and were generally found at elevations higher than 300 m. These were clearwater systems with a median DOC of 1.1 mg/l and Al_{im} of 202 µg/l.

Based on results from this survey six "high-interest regions" were identified that contained most of the acidic lakes and streams identified in the NSWS. While the combined high-interest lakes populations included only 26% of the all NSWS lakes, they included 95% of all inorganic acidic lakes. Similarly, 37% of all NSS upstream reaches were in the high-interest population, but 84% of all inorganic acidic NSS upstream reach ends were included. The six areas targeted were

- SOUTHWEST ADIRONDACK MOUNTAINS: Within this subpopulation, 38% of the lakes were acidic (ANC≤0 µeq/l) and 51% had closed-system pH of 5.5 or less. These acidic lakes are typically rapidly flushed drainage lakes in which SO_4^{2-} is the dominant anion and DOC concentrations ranged 3 to 4 mg/l. Many had high concentrations of inorganic monomeric Al, with 36% having Al_{im} greater than 100 µg/l.

- NEW ENGLAND: Within this subpopulation 4.7% of the NSWS lakes had ANC≤0 µeq/l and 6.8% had pH≤5.5. In the Seaboard Lowlands area 7.7% of the NSWS lakes were acidic (ANC≤0 µeq/l). The majority of the acidic lakes in this region were dominated by inorganic acids, but about one-fifth, mostly in the Seaboard Lowlands, were dominated by organic acids.

- FORESTED MID-ATLANTIC HIGHLANDS (A.K.A., MID-APPALACHIAN REGION): Within the stream populations, 11.5% were acidic and 16.7% had closed-system pH≤5.5. Among lakes of this subpopulation, 10% had ANC ≤0 µeq/l and 9% had pH≤5.5. Acidic surface waters of this subpopulation typically had low DOC (stream mean of 1.5 mg/l, lake mean of 2.6 mg/l) and high SO_4^{2-} concentrations (stream mean of 148 µg/l, lake mean of 122 µg/l). All acidic lakes and streams were dominated by inorganic acids, with SO_4^{2-} being the dominant anion with relatively low NO_3^- concentrations (mean < 10 µeq/l). Acid streams had the highest concentrations of inorganic monomeric Al of all high interest areas, with a mean Al_{im} of 202 µg/l. Acid lakes had a mean Al_{im} of 77 µg/l.

- ATLANTIC COASTAL PLAIN: At their upstream ends, 14% of the NSS stream reaches were acidic (ANC≤0 µeq/l) and 17% had pH of 5.5 or less. Both mineral and organic acids provided important contributions in the acid-base status in these streams. Among the acidic streams, 65% were dominated by organic acids, while 32% were dominated by inorganic acids. Acidic streams in the New Jersey Pine Barrens were dominated by inorganic acids, but with considerable influence by organic acids, and were similar to organic acid dominated streams. In the rest of the region, NSS streams were dominated by organic acids. Twenty acidic lakes identified on Cape Code were dominated by chloride and had salt water SO_4^{2-} concentrations of 110 to 175 µeq/l.

- NORTHERN FLORIDA HIGHLANDS: This subregion includes the Central Lake District (Trail Ridge) north of 29°N latitude and the Panhandle. For this subregion, 63% of the lakes were acidic (ANC≤0 µeq/l) and 52.6% had closed system pH of 5.5 or less. Most (90%) of the acidic lakes were seepage lakes. Of the acidic lakes, 80% were dominated by inorganic acids, with median SO_4^{2-} concentrations of 83 µeq/l, median DOC of 2.4 mg/l, and mean Al_{im} concentrations of 39 µg/l. Acid streams had low ionic concentrations (mean base cation of 21µg/l, SO_4^* of 16 µeq/l). Three-quarters of the acid streams were

dominated by inorganic acids, with DOC of less that 2 mg/l.

- LOW-SILICA LAKES IN THE EASTERN UPPER MIDWEST: This subregion includes lakes in northeastern Wisconsin and the Upper Peninsula of Michigan having silica concentrations of less than 1 mg/l. Of these lakes, 15.9% were acidic (ANC≤0 μeq/l) and 19.3% had closed-system pH of 5.5 or less. Of these acidic lakes, 80% were seepage lakes, with low silica concentrations reflecting the lack of well-buffered ground water inputs. Inorganics dominated the acidity in 87% of these lakes. SO_4^{2-} was generally the dominant anion, with a mean concentration of 69 μg/l. DOC concentrations were relatively high (mean of 3.9 mg/l), indicating substantial influences by organic acids. Al concentrations were low.

SOS/T REPORT 10: WATERSHED AND LAKE PROCESSES AFFECTING SURFACE WATER ACID-BASE CHEMISTRY

1. Atmospheric deposition is often an important, yet highly uncertain, component of the acid-base budget in many watersheds and in lakes and streams having low ANC. Greatest uncertainty is in regions holding high elevation or rough terrain and for the processes of particulate and gaseous deposition. The uncertainty in nitrogen deposition is less important to acid-base budgets compared with internal fluxes. The uncertainty in base cation deposition may cause large uncertainty in acid-base budgets in some watersheds.

2. Watersheds having a greater proportion of their water flowing through shallow, more acidic soils tend to have more acidic and lower ANC surface waters than watersheds in which a large proportion of the water flows through deeper, more weatherable materials. This conclusion is generally valid for baseflow chemistry and for episodic changes in acid-base chemistry for surface waters. The major pathways for movement of water through watersheds are subsurface flows, even during most extreme flow events. Generally, overland flow is rarely observed.

3. Even without acidic deposition, the natural sequence in watershed development is one of soil acidification associated with base cation accumulation in biomass (i.e., in vegetation and humus), an increase in soil cation exchange capacity, and increased leaching of soluble or weatherable materials from upper soil horizons.

4. Naturally acidic lakes and streams dominated by organic anions occur predominantly in areas where bedrock or unconsolidated sediments are highly resistant to weathering. Most are in regions with large buildups of organic matter (e.g., areas with spodic soils and in wetlands), often in more northern and coastal plain regions having low-relief terrain and relatively poor drainage.

5. Adsorption-desorption properties of soils in the watershed regulate export of atmospherically deposited SO_4^{2-} into surface waters. Vegetation has only a limited capacity to immobilize SO_4^{2-}, even under optimal conditions. Great uncertainty still exists regarding the reversibility of SO_4^{2-} adsorption and critical factors controlling desorption. But, at least one documented study that examined adsorption-desorption across a variety of soils showed that most soils exhibited some degree of irreversible adsorption.

6. The extent to which atmospheric nitrogen deposition affects the export of NO_3^- from watersheds depends on biological rather than geochemical process in the watershed. Most forest soils (including those that are not currently affected by nitrogen deposition leading to increased nitrogen accumulation and possible saturation) have the potential to produce and leach NO_3^- to surface waters.

7. Sulfate deposition often causes an anion shift from drainage water compositions dominated by HCO_3^- and organic anions to one dominated by SO_4^{2-}.

8. The relative mix of cations in soil solution depends on the mix of cations on soil exchange sites (i.e., soil base saturation) and cation selectivities of the exchange sites. In extremely acid soils (i.e., less than 10% base saturation), Al and H^+ dominate the cations in solution, resulting in reduced ANC concentrations in drainage waters from the watershed; in less acid soils (i.e.,

greater than 20% base saturation), base cations dominate and ANC remains unaltered. Data on soil chemistry and mineralogy, bedrock mineralogy, and water flow paths are all necessary to predict the chemistry of waters draining terrestrial systems.

9. Water quality changes that occur when soil water rich in CO_2 flows into surface waters depend on ANC in both waters. If SO_4^{2-} and NO_3^- from deposition produce negative ANC in the soil solution, the pH effects observed within the soil solution may be minimal but the consequential change produced by discharge of this low pH and high Al soil water to surface water may be substantial.

10. Many seepage lakes (lakes having no stream input) that receive even 5% of their total water input from groundwater are seldom likely to be affected by acidic deposition to their surfaces. That is, ANC supplied by a small proportional volume of ground water is often sufficient to neutralize incident acidic precipitation. The chemistry of seepage lakes that derive greater than 95% of their input from precipitation are greatly influenced by incoming precipitation.

11. Numerous processes modify the acid-base chemistry of water entering lakes and streams, including base cation production and SO_4^{2-} and NO_3^- retention. These process occur in all systems, but rates for these processes vary among systems. For example, those systems having long residence times and relatively deep mean soil depths tend to have the greatest influence on acid-base chemistry in their drainage waters. Further, in some lakes, more ANC is derived from in-lake production than that generated within the terrestrial watershed. The most important in-lake processes generating ANC are likely to occur in the sediment rather than the water-column of acid-sensitive lakes.

SOS/T REPORT 11: HISTORICAL CHANGES IN SURFACE WATER ACID-BASE CHEMISTRY IN RESPONSE TO ACIDIC DEPOSITION

1. The role of acidic deposition as a cause of acidic surface waters is supported by numerous lines of evidence, including the current chemical composition of acidic surface waters, extensive paleolimnological analyses of bottom sediment deposits, the worldwide distribution of acidic surface waters, experimental studies, monitoring and re-survey data, and principles of geochemistry.

2. Acidification of low pH and low ANC ($\leq$ 50 μeq/l) Adirondack lakes has been less than previously believed because of considerable watershed and in-lake neutralization of acidic inputs via enhanced base cation mobilization.

3. Outside the Adirondack Mountains, the chemistry of drainage lakes and streams in several areas is consistent with the hypothesis of acidification of sensitive systems by acidic deposition. This is most notable for the Poconos/Catskill subregion, the Mid-Atlantic Highlands (i.e., mid-Appalachians), the eastern portion of the Upper Midwest, and the New Jersey Pine Barrens.

4. The chronic acid-base character of lakes in Maine has been generally unaffected by acidic deposition. Chemistry of acidic streams in the Mid-Atlantic Coastal Plain, outside the New Jersey Pine Barrens, in most cases, suggest acidification due to organic acidity and not acid deposition effects. Chronic acidification of western lakes from acidic deposition has not apparently occurred.

5. The acid-base character of acidic streams in the Florida Panhandle can be ascribed to a combination of organic acidity, marine cation retention, and near zero weathering inputs to some systems. For some waters, acidic deposition may also have provided minor contributions.

6. In the Upper Midwest, the chemistry of sensitive (ANC$\leq$50 μeq/l, $SiO_2 \leq 1$ mg/l) seepage lakes exhibit both increasing sensitivity (lower base cation concentrations) and increasing effects from acidic deposition across a longitudinal gradient from west to east. In the Upper Peninsula of Michigan, 15% of the lakes are of this type and many of these are currently acidic because of high SO_4^{2-} relative to base cation concentrations. These lakes have probably been acidified by acidic

deposition. Throughout most of the Upper Midwest, however, substantial regional acidification of lake water from acidic deposition has not occurred.

7. Most lakes and streams in the United States, especially those that have current ANC greater than about 50 μeq/l, have probably not had declines in pH or ANC within their recent histories.

SOS/T REPORT 12: EPISODIC ACIDIFICATION OF SURFACE WATER ACID-BASE CHEMISTRY

1. Episodic acidification is the process by which lakes and streams develop short-term decreases in ANC, usually during hydrological events and over time scales of hours to weeks. Episodes are stochastic or probabilistic in nature, in terms of occurrence, frequency, intensity, duration, and, to some extent, composition.

2. Episodic acidification is practically a ubiquitous process in streams and drainage lakes. Presently, data are not available that allow rigorous population estimates of episodic acidification in the United States to be completed. Most states plus southeastern Canada, however, where monitoring data have been collected, display characteristics of episodic acidification.

3. Episodic acidification is controlled by a combination of natural and anthropogenic factors. The relative importance of these factors varies among regions and among watersheds within regions. There are three primary natural process that can produce episodes: (1) dilution, (2) nitrification, and (3) organic acid production.

4. Episodic acidification is not symptomatic of human caused chronic acidification.

5. The severity (minimum ANC or highest dissolved aluminum) of episodes is increased by acidic deposition in some areas.

6. While improvements in water chemistry during episodes in some lakes and streams would be expected, especially in the Northeast and Mid-Atlantic, this issue has not been addressed by scientific investigations. The roles of nitrogen and sulfur deposition and of organic acids in causing episodic acidification all need to be examined.

7. Modeling episodic acidification in surface waters has been only moderately successful, primarily because of a lack of data and a lack of understanding of important hydrological flow and biogeochemical process.

SOS/T REPORT 13: BIOLOGICAL EFFECTS OF CHANGES IN SURFACE WATER ACID-BASE CHEMISTRY

1. The most important chemical properties of surface waters influencing biological responses to acid-base chemistry are pH, inorganic monomeric aluminum, and calcium. Decreases in pH (particularly below 6.0-6.5) and increases in the concentration of inorganic monomeric aluminum (above 30-50 μg/l for the most sensitive organisms) can increasingly cause adverse biological effects. Small changes in calcium are particularly important at low calcium concentrations (< 100-150 μeq/l).

2. A number of the species that commonly occur in surface waters susceptible to acidic deposition cannot survive, reproduce, or compete in acidic waters. Thus, with increasing acidity, these "acid-sensitive" species are eliminated and species richness (the number of species living in a given lake or stream) declines. These changes in aquatic community structure are found to begin in many surface water systems as chronic pH levels drop below the range of about 6.0 to 6.5. Acid-sensitive species occur in all major groups of aquatic organisms. Both chronic and episodic acidification can affect aquatic organisms, with chronic acidification perhaps the primary cause of continuing effects in acidified lakes and episodic acidification being particularly important case of effects in streams.

3. System level processes, such as decomposition, nutrient cycling, and productivity, are fairly robust and affected only at relatively high levels of acidity (e.g., chronic pH<5.0-5.5).

4. Relatively few studies have been conducted on the recovery of biological communities following reduction of acid

inputs. Based on our current understanding of the processes of biological response, decreases in indicateity would be predicted to likely allow acid sensitive species and species richness both to increase in acid affected surface waters.

5. Laboratory toxicity experiments and field surveys provide and adequate basis for quantifying the relationship, on a regional scale, between changes in pH, aluminum, and calcium and acidity-induced stress on fish populations. Thus, toxicity-based models, field based models, and models that combine laboratory and field data can be used to evaluate the biological significance of projected changes in acid-base chemistry given alternative deposition and emissions scenarios.

6. The loss of fish populations and/or absence of fish species as a result of acid-base chemistry changes has been documented for some lakes and streams in several regions of the United States. Application of fish response models suggest that the percentage of NSWS waters with acid-base chemistry unsuitable for the survival of acid-sensitive fish species range from less than 5% in areas such as the Upper Midwest to near 60% for upper stream reaches in the Mid-Atlantic Coastal Plain. An estimated 23% of the Adirondack lakes and 18% of the mid-Appalachian streams classified as potential brook trout habitat currently have acid-base chemistry unsuitable for brook trout survival.

SOS/T REPORT 14: METHODS FOR PROJECTING FUTURE CHANGES IN SURFACE WATER ACID-BASE CHEMISTRY

1. The Direct/Delayed Response Project (DDRP) approach utilized the best available procedures for projecting the effects of sulfur deposition on future changes in surface water acid-base chemistry for target populations of lakes in the Northeast, Upper Peninsula of Michigan, and Florida and streams in the mid-Appalachians and Southern Blue Ridge Province.

2. Several models provide credible projections of selected subpopulations of target lakes.

3. Measurement, parameter, input, and population extrapolation error can be quantitatively estimated for model projections, but aggregation and model assumption error can be estimated only qualitatively. Results from individual watershed projects can be extrapolated through the probability sampling frame for regional estimates of population attributes.

4. Although there are remaining uncertainties with respect to structural error, aggregation, and long-term projection confirmation, model projections are the only feasible approach for comparing the effects of different illustrative emissions control scenarios on future changes in surface water acid-base chemistry.

SOS/T REPORT 15: LIMING ACIDIC SURFACE WATERS

1. Liming can effectively mitigate many of the adverse ecological effects of surface water acidification independent of reduction of acidifying emissions.

2. Conventional whole-lake liming is a more established mitigation alternative than liming running waters and watersheds.

3. Liming surface waters commonly results in significant positive and predictable physiochemical changes in aquatic ecosystems.

4. Liming generally increases nutrient cycling, decomposition, and primary productivity and results in positive responses in fish and other aquatic biota.

SOS/T REPORT 16: CHANGES IN FOREST HEALTH AND PRODUCTIVITY IN THE UNITED STATES AND CANADA

1. The vast majority of forests in the United States are not affected by decline.

2. There is experimental evidence that acid deposition and associated pollutants can alter the resistance of red spruce to winter injury; through this mechanism, acidic deposition may have contributed to red spruce decline at high elevations in the northern Appalachians. Evidence of red spruce decline and pollutant involvement in the southern Appalachians is less substantial.

3. Most sugar maple trees and stands in the United States and Canada are not affected by decline. Sugar maple declines are significant problems, however, in Quebec and in some parts of Ontario, Vermont, and Massachusetts. Natural stresses including nutrient deficiencies and defoliation by insects are important factors in these declines. Involvement of acidic deposition and/or ozone as significant contribution or predisposing factors have not been demonstrated, but such involvement cannot be ruled out on the basis of available information.

4. A regional decline of southern pines has not been demonstrated. The reported growth rate reductions in certain classes of trees and stands are not fully understood, however, and require further investigation. The occurrence of reduction in tree growth rates in natural pine stands is an expected consequence of historical land use patterns, increases in stand age and competition, and other non-pollutant factors. Available information is not adequate to determine whether the magnitude of reported growth reduction is greater or less than would be expected in the absence of acid deposition and associated pollutants. Results of exposure-response experiments indicate that ozone at ambient concentrations can alter growth and physiology of southern pines seedlings and justify concern about adverse effects of ozone on the health and productivity of southern pine forests.

5. Compared to ozone and many non-pollutant stress factors, acidic deposition appears to be a relatively minor factor affecting the current health and productivity of most forest in the United States and Canada. Most of these forests are receiving acidic depositions at doses that have not had a serious impact on health and productivity. The possibility of long-term (several decades) adverse effects on some soils appears realistic. Sulfate deposition increases leaching losses of nutrient cations from many different forest soils and over the long term may reduce the fertility of soils with low buffering capacities or low mineral weathering rates.

SOS/T REPORT 17: DEVELOPMENT AND USE OF TREE AND FOREST RESPONSE MODELS

1. The models presented in this report are preliminary, and they emphasize our lack of knowledge about fundamental tree and forest processes. Nonetheless, consideration of the dynamics of implied by what we do know of the processes indicate that considerable caution is needed in projecting long-term effects from acidic deposition and ozone. In particular, long-term dynamics generated by synergies, and compensations between mechanisms, can produce threshold effects. The possible existence of these threshold effects implies that simple projections will not be adequate to capture long-term effects of acid deposition. Therefore, the null hypotheses of no long-term effect should not be accepted without caution, even if it appears warranted by the current data and theory.

SOS/T REPORT 18: RESPONSE OF VEGETATION TO ATMOSPHERIC DEPOSITION AND AIR POLLUTION

1. Based on crop-effects research conducted by NAPAP and other research programs, acidic precipitation at ambient levels in the United States has not been shown to be responsible for regional crop yield reduction.

2. Ambient fog acidity concentrations are not great enough to reduce the yield of agricultural crops, but under certain localized conditions may occasionally be high enough to cause visible injury to plant tissue and thereby reduce the marketability of sensitive crops.

3. Ambient SO_2 concentrations by themselves are not responsible for regional-scale crop yield reductions in the United States.

4. Nitrogen dioxide at ambient concentrations is not a direct source of regional-scale growth or yield reduction in U.S. agricultural crops.

5. Although pollutant mixtures (e.g., SO_2 + O_3, or SO_2 + NO_2) are of undetermined important on a national scale, at least in some regions (e.g., Ohio River Valley), ambient air quality monitoring suggests

the potential for effects from mixed exposures.

6. There is evidence that acidic cloud water in combination with other stresses affects some high elevation spruce forests in the eastern United States.

7. Long-term changes in the chemistry of some sensitive soils is expected from acidic deposition, but it is uncertain whether this will result in reduced forest health, how effects will be manifest, how much of the forest resources will be impacted, or how long it will take for such effects to occur.

8. There is no conclusive evidence that acidic precipitation is a major causal factor in sugar maple decline, but in limited areas where nutrient deficiency symptoms are currently evident, acidic deposition could further exacerbate their expression.

9. Ambient SO_2 concentrations are not responsible for regional-scale growth reductions in the United States.

10. Nitrogen dioxide at ambient concentrations is not a direct source of regional-scale growth reduction in forests of the United States.

11. The same concern about possible effects from pollutant mixtures discussed for crops (Conclusion 5, above) applies to forests.

APPENDIX B

SELECTED PLOTS FROM EPA'S NITROGEN BOUNDING STUDY

APPENDIX B

SELECTED PLOTS FROM EPA'S NITROGEN BOUNDING STUDY

INTRODUCTION

The Nitrogen Bounding Study (NBS)[1] is one of several recent and ongoing studies conducted by the U.S. Environmental Protection Agency (EPA) to investigate aquatic and terrestrial effects of acidic deposition. This study was initiated to address a major issue that arose during EPA's completed Direct/Delayed Response Project (DDRP), namely to investigate the role of nitrogen compounds in the soil water and surface water acidification within forested watersheds. Models and analyses used during the DDRP focused on sulfur deposition and its effects on water chemistry, but effects due to nitrogen cycling received much less attention. That difference in focus was due to the general lack of quantitative knowledge regarding nitrogen transformation processes in soils. In addition, evidence available when the DDRP was designed and initiated primarily indicated that most deposited atmospheric nitrogen is taken up and held by biota, thus making little contribution to acidification. More recent evidence suggests, however, that some forest catchments in the eastern United States, for example, can become nitrogen saturated and that nitrogen leaching from these systems can contribute substantially to lake and stream acidification, particular during runoff episodes. While several long-term studies intended to address the role of nitrogen deposition in surface water acidification are under way, the NBS was intended to provide near-term information on which to "bound" likely relationships for nitrogen *and* sulfur deposition on surface-water acidification responses.

The NBS evaluated target populations of surface waters in three sensitive geographic regions: lakes in the Adirondack Region and stream reaches in the Mid Appalachian Region and the Southern Blue Ridge Province. Model projections completed during the NBS used a modification of the Model of Acidification of Groundwater in Catchments (MAGIC), the model of current choice for assessing many watershed processes associated with acidic deposition. It includes a minimum number of critical chemical and hydrological processes occurring in watersheds to simulate soil solution and surface water chemistry, and to project average monthly or annual concentrations of acid-base chemistry in surface water. Primary input data for its use in NBS came from the National Surface Water Survey (NSWS), the DDRP, and updated deposition information from EPA atmospheric modeling studies discussed in Chapter 3 of this report.

Nitrogen uptake parameters in the model were used to provide simple surrogates for complex processes within the nitrogen cycle. That is, these parameters were adjusted to yield "best case" (i.e., maximum nitrogen retention in the biota within a watershed) and "worst case" (i.e., complete nitrogen saturation in the biota within a watershed) approximations to estimate the resulting combined effects by nitrogen and sulfur deposition on lake and stream acidity. Thus, model results provide upper and lower bounds on the levels of acidification that more realistic models (currently under development) would likely project.

The NBS projected surface water chemistry for two target years (years 2015 and 2040) using the assumption that emissions reductions of 10 million tons SO_2 and 2 million tons NO_x mandated by the 1990 Clean Air Act Amendments of (CAAA) were fully implemented. As such, deposition rates for sulfur and nitrogen were assumed to equal those projected by atmospheric models to accompany emissions reductions with full CAAA implementation at the year 2010 and that these rates would be attained by the year 2020.

After the year 2010, the NBS defined different deposition scenario projections for years between the years 2010 and 2020 using SO_4^{2-} and NO_3^- deposition rates that decline linearly from the common year 2010 rates to a selection of different modeled year 2020 deposition rates for each scenario modeled. For example, some modeled scenarios maintained the 2010 deposition rates through the year 2020, while some alternative

[1] Van Sickle, J., M.R. Church. 1995. *Methods for Estimating the Relative Effects of Sulfur and Nitrogen Deposition on Surface Water Chemistry.* U.S. Environmental Research Laboratory, Corvallis, OR.

modeled scenarios decreased the year 2010 rate to background deposition rates only by the year 2020. Rates for still other modeled scenarios decreased to levels between these extremes. (*Background deposition* rates are those materials that originate from only natural, agricultural fertilizer, and domestic livestock sources.) Each modeled deposition rate was then assumed to remain constant at the specific modeled 2020 rate until the year 2040, the end of the model projection period. The selected plots from the NBS contained in this appendix include model projections for the years 2015 and 2040. The 2040 plots were primarily depended upon for the review and conclusions from the NBS presented in Chapter 2 of this report.

In examining the NBS plots it is first important to recognize that the plotted response surfaces represent only projected proportions for the subpopulations of sensitive surface waters modeled by the NBS; they do not represent responses for either all surface waters or for all NSWS sampled surface waters in the modeled regions. Each page holds four NBS plots displaying projected response surfaces over ranges of possible sulfur and nitrogen deposition rates at the year 2040. Each of the four plots represent one of the four possible durations used to bound likely alterative times to watershed nitrogen saturation: 50 years, 100 years, 250 years, and never (i.e., assumes nitrogen uptake remains constant into the future at recently estimated rates).

Sets of pages are grouped within the three modeled regions, (1) Adirondacks Region, (2) mid-Appalachian Region, and (3) Southern Blue Ridge Province. Within the 10 pages for each region, one each is presented for projections of relative proportions of lakes with ANC≤0 μeq/l, ANC≤50 μeq/l, pH≤5.0, pH≤5.5, and pH≤6.0 over the ranges of sulfur and nitrogen depositions assessed for each region and for each of the four bounding times to watershed nitrogen saturation, for the years 2015 and 2040.

INTERPRETING THE NBS PLOTS

To illustrate interpretation of the NBS plots, the first page of year 2040 plots shows projected percentages of NBS target population lakes in the Adirondack Mountains having ANC of 0 μeq/l or less, under assumptions of four bounding times to watershed nitrogen saturation equal 50, 100, and 250 years, and never (i.e., constant). Response contours for each plot show how percentages of target waters are projected to relate to possible differences in total sulfur and nitrogen deposition loading rates throughout the modeled ranges for these depositions. For these plots, deposition ranges for the year 2040 begin at projected background deposition rates for sulfur and nitrogen (1 kg S/ha/yr and 4 kg N/ha/yr) and extend to their maximum modeled concentrations (7.5 kg S/ha/yr and 11.3 kg N/ha/yr), which are the rates projected to accompany full implementation of the 1990 CAAA.

Thus, the plots on page B-10 shows NBS projections for proportions of Adirondack lakes having ANC≤0 μeq/l. The upper right plot shows projections for an assumed 100 years to watershed nitrogen saturation. Here, in the upper right corner of this upper right plot, model projections estimate that approximately 26 percent of the target Adirondack lakes may be acidic (ANC≤0 μeq/l) in the year 2040 for modeled sulfur and nitrogen deposition rates projected to accompany implementation of the 1990 CAAA. With only "background" deposition of sulfur and nitrogen, as shown in the lower left corner of the upper right plot, 3.4 percent of these target lakes are projected to be acidic in 2040.

In reviewing these plots, it is helpful to recognize that several relationships generally apply to all of them:

- The slopes of contour lines in each of the NBS response plots reflect the relative importance of sulfur and nitrogen in causing the projected response relationships. Nearly vertically plotted response contours indicate that the projected ANC response is attributable primarily to sulfur deposition. Nearly horizontal plotted response contours indicate the plotted ANC response is attributable primarily to nitrogen deposition. A forty-five degree diagonal contour indicates equal contributions by both sulfur and nitrogen depositions.
- Changes in the spacing between individual response contours within each plot appears to be attributable to patterns in sample weighting during model projections, rather than due to some intrinsic character of the deposition-response relationships.
- The density of response contours across the modeled deposition ranges for each plot directly relates to the potential average responsiveness by target waterbodies to po-

tential changes in sulfur and nitrogen deposition rates on the specified water quality classification variable modeled (e.g., ANC≤ 0 μeq/l). Therefore, plots with a high density of contour lines depict a high level of responsiveness to future possible changes in deposition rates.

- In general, modeled ANC responses to reductions in sulfur deposition found during the NBS appear to be linear and proportionally equivalent across the ranges of modeled sulfur reductions. Additional investigation may help to determine whether this relationship is due to actual environmental functions or to some artifact inherent in the model's application.

In considering possible individual extrapolation of the results presented with these plots, beyond that presented in the preceding chapters, care must be taken to ensure that these results are not over extrapolated. That is, in applying the NBS model results, as is the case when applying any simulation modeling results, it is important that the assumptions underlying the modeling be understood and carefully considered relative to additional conditions or systems to which they are to be applied. In doing this, the modeled processes should be described and evaluated to determine how well they correspond to the system (e.g., watershed) for which the application is intended. In general, models should only be applied to (i.e., *constrained* to) systems, conditions, and assumptions that fall within or very near the boundaries of those used to develop the model. Whenever models are applied outside these boundaries, the consequences of knowingly violating the model's constraints should be assessed as part of the model analysis. Unfortunately, violation of model assumptions cannot always be readily known or easily assessed. Nevertheless, when model constraints are not met by the natural processes modeled or by the data collected for model input, model projections typically will deviate from reality. The magnitude of such deviations contribute markedly to what is generally called model *uncertainty*. Reasons why watershed models, including MAGIC, are particular difficult to design and test include the following.

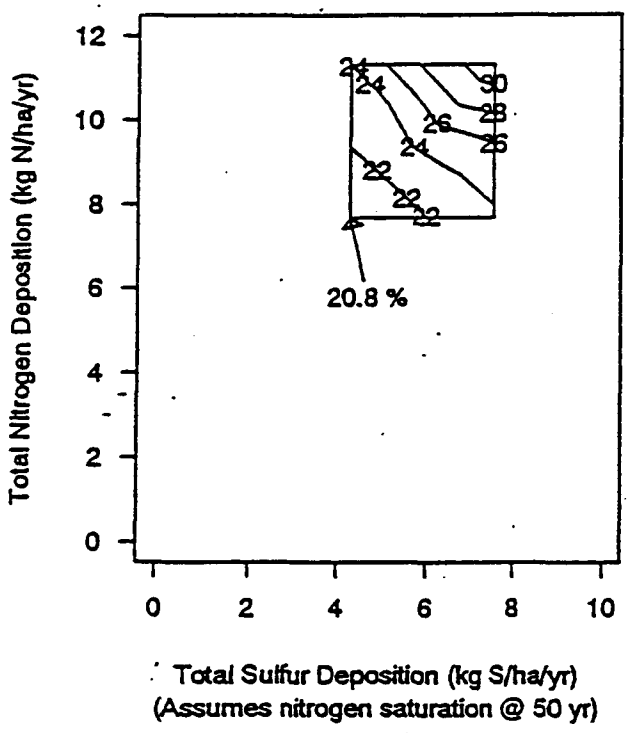
- Processes controlling watershed functions are very difficult to observe either in nature or in any laboratory experiment. Thus, these processes may be either virtually unknown or inaccurately represented in the model, i.e., the model might not be a "true" model.
- Actual conditions within individual watersheds that determine processing or transfer rates may be unknown or poorly quantified. Consequently, the model might be poorly *parameterized,* i.e., the modeled parameters may be poorly adjusted or calibrated to approximate parameters actually occurring within the modeled system.
- Inputs to the models can be poorly known or unable to be accurately predicted (e.g., dry deposition loads to a watershed).
- Models often are difficult to test. That is, models may be largely "unverified," "unconfirmed," or "unvalidated." In fact, it is often argued that a model can never be confirmed to be true, it can only be falsified by failing to accurately project some outcome. Further, when a model does accurately predict an outcome, its validity is not proven, because the "right" result may have been projected for the wrong reason.

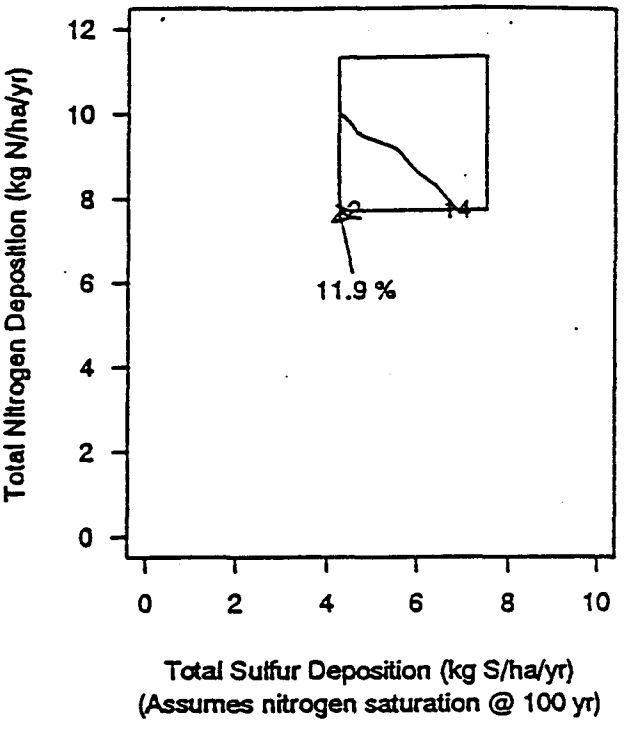
Further, it is useful to remember that environmental monitoring and simulation modeling have complementary environmental assessment roles. Effects monitoring (i.e., surface water chemistry) is necessary to determine the actual effects of acidic deposition rates on environmental resources and to provide data needed to develop and test models. In turn, simulation modeling is useful to project potential differences among future deposition or environmental scenarios. This is particularly true for projections of acidic deposition effects because no set of monitoring records of sufficient length exist that allow establishing a clear statistical relationship linking changing historic ecological responses to changing acidic deposition input rates. Without this historic record it is not possible statistically to project future changes, i.e., we cannot predict the future directly from the past because we do not know the past.

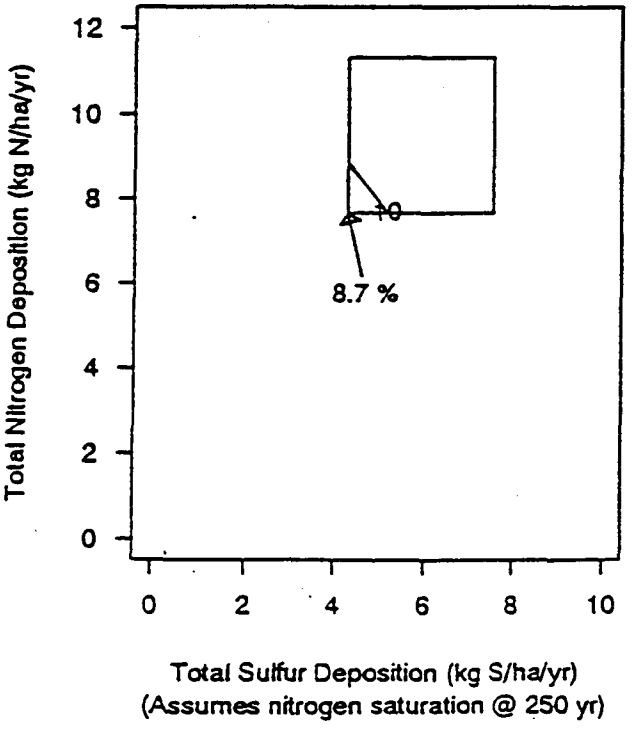
Simulation models, such as the MAGIC model, generally do not require well quantified historical relationships to provide potentially useful projections of future conditions. But watershed simulation modeling, including the NBS, often continues to include significant uncertainties, as noted in the above paragraphs and in Chapter 2. This is especially the case regarding the modeling of nitrogen cycling within watersheds and the po-

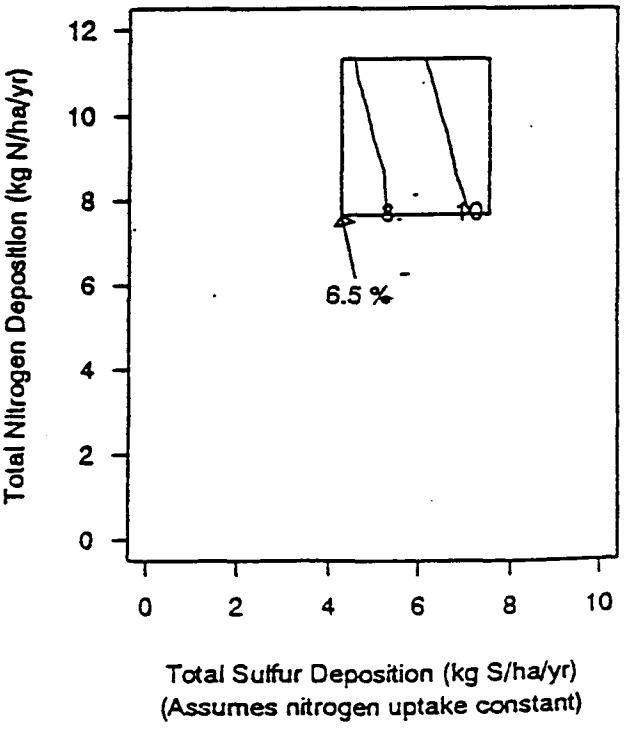
tential acidifying effects of nitrogen deposition on soils, watersheds, and associated surface waters. Additional uncertainties also remain regarding exactly which processes to include in such models and about how such processes should be linked within these models. Further, there is almost a complete dearth of monitoring and survey information on the regional distributions of watershed characteristics that would allow such models to be calibrated and applied to project future effects. Improving capabilities to model these relationships will lead to better projections of potential future environmental effects from both sulfur and nitrogen deposition. Present knowledge of nitrogen cycling and early steps toward nitrogen modeling provides a solid foundation for more important and productive advances in this field. These advances, particularly, would lead to significantly reduced uncertainty in potential future effects of nitrogen.

Percent of target population lakes with ANC<=0,
Adirondacks Region at Year 2015
where deposition=median regional @ year 2015.

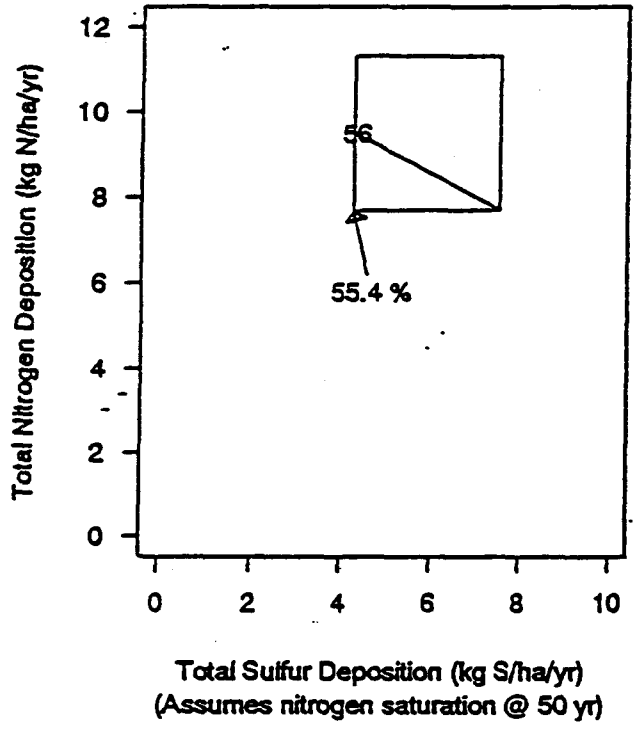


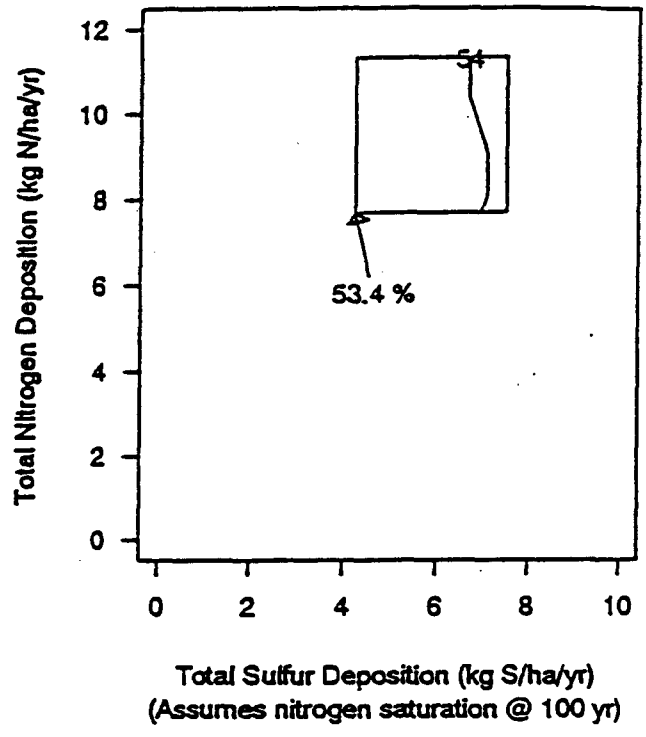


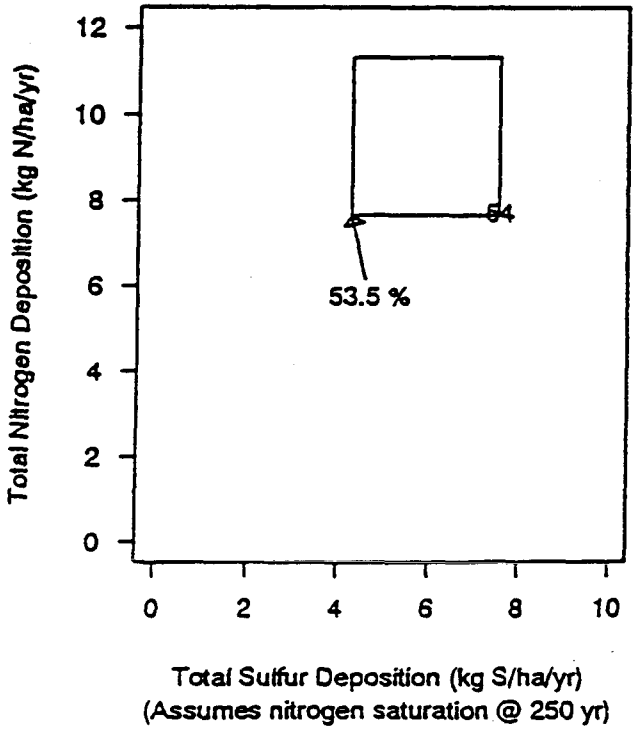


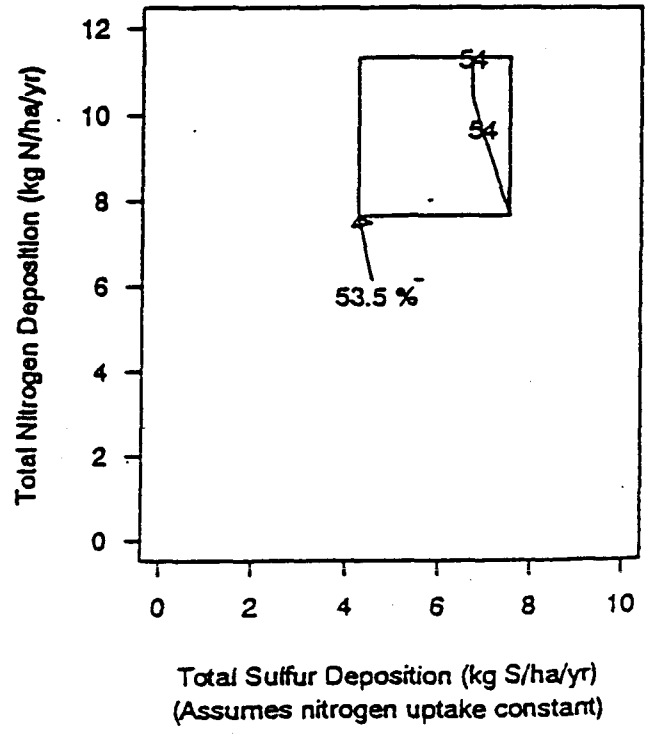


Percent of target population lakes with ANC<=50,
Adirondacks Region at Year 2015
where deposition=median regional @ year 2015.

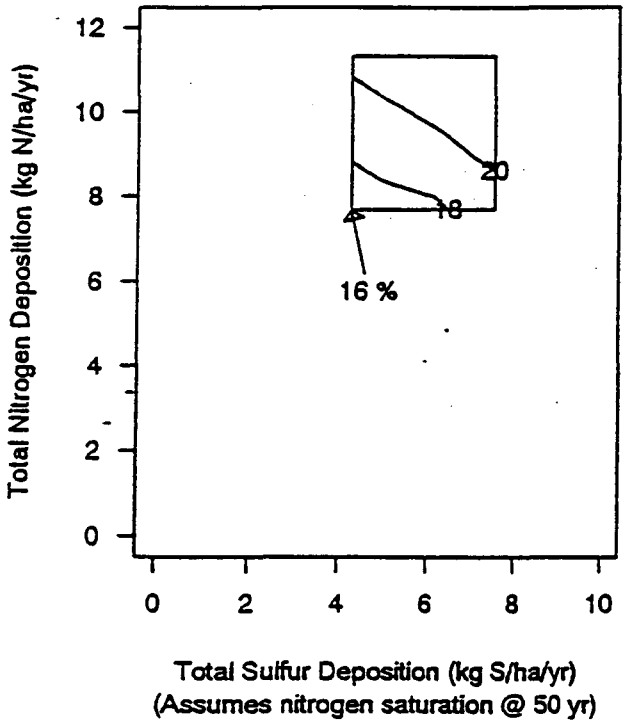


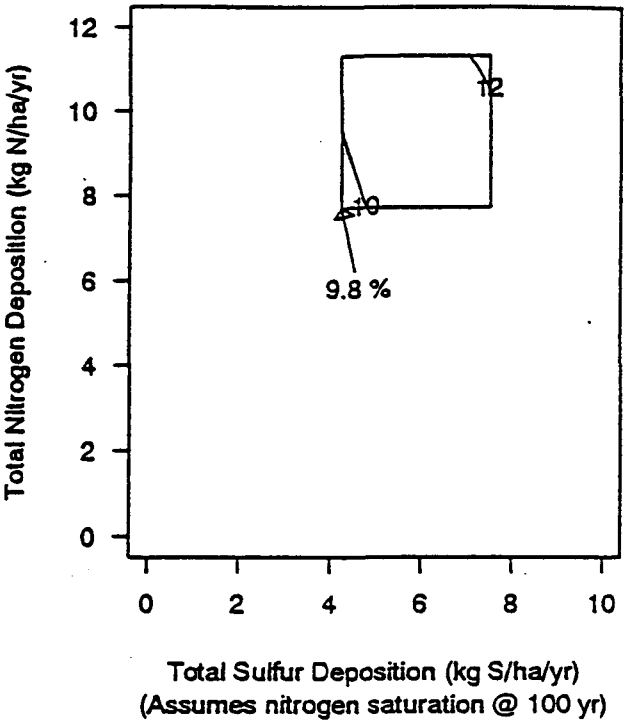


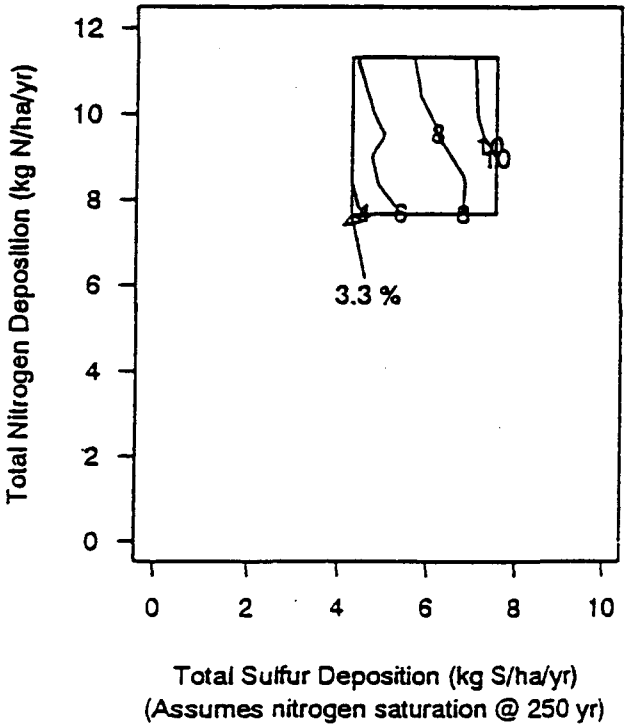


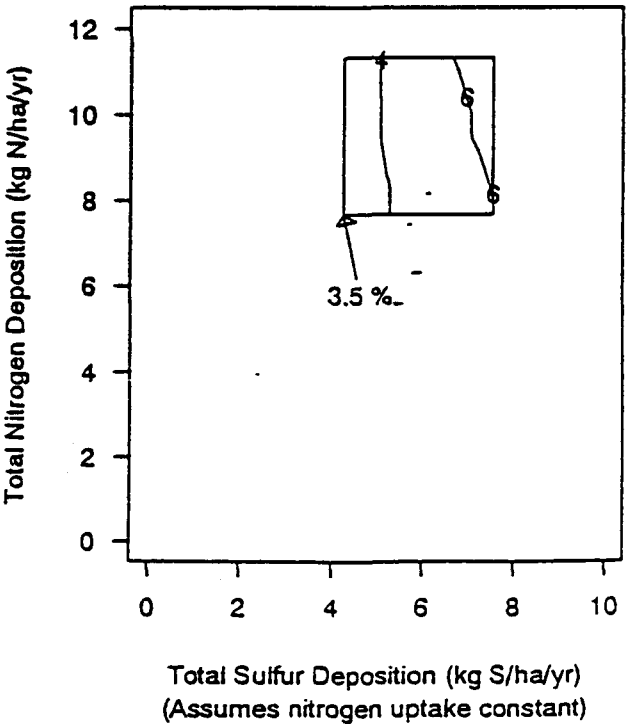


Percent of target population lakes with pH<=5.0,
Adirondacks Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

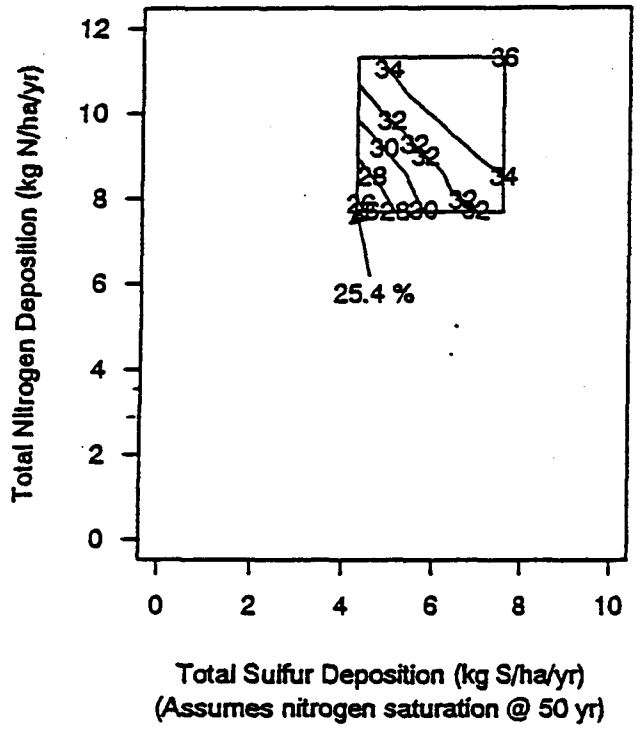


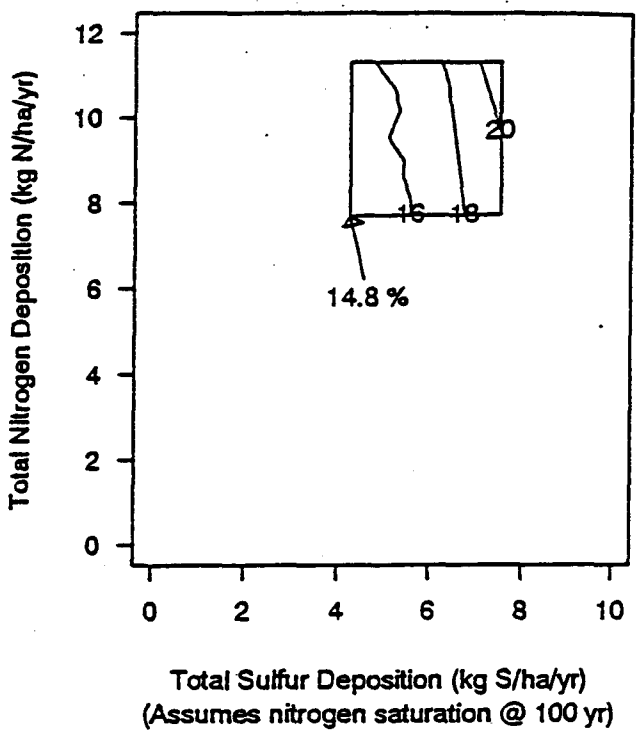


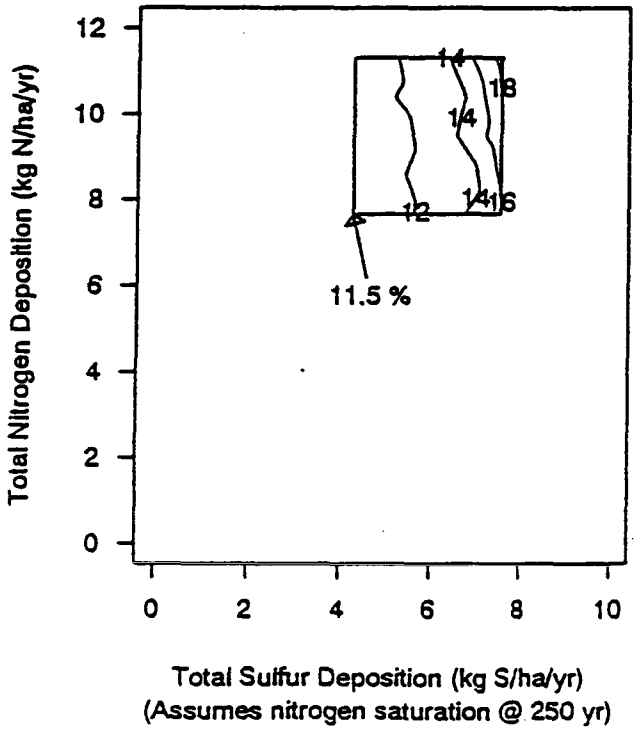


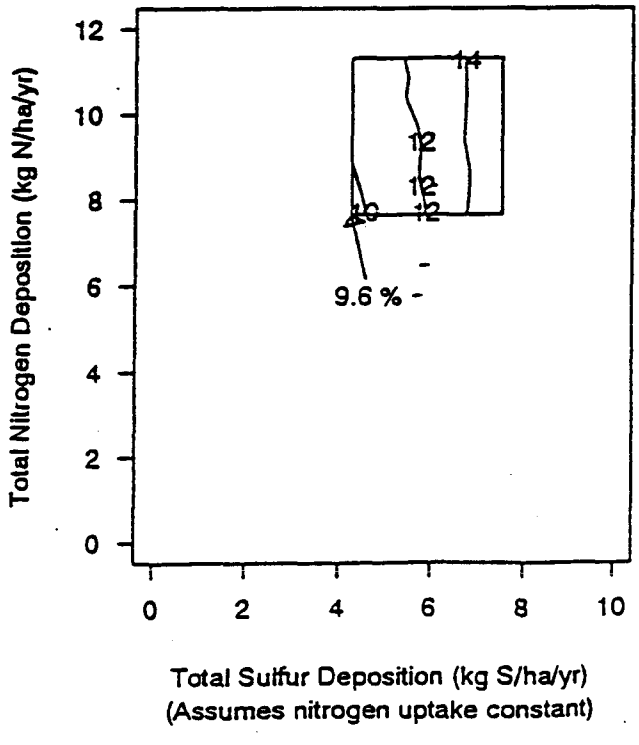


Percent of target population lakes with pH<=5.5,
Adirondacks Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

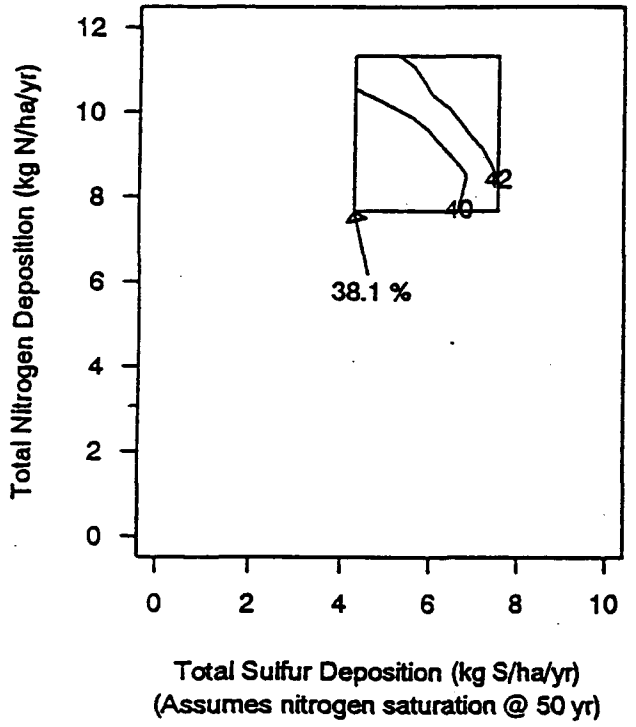


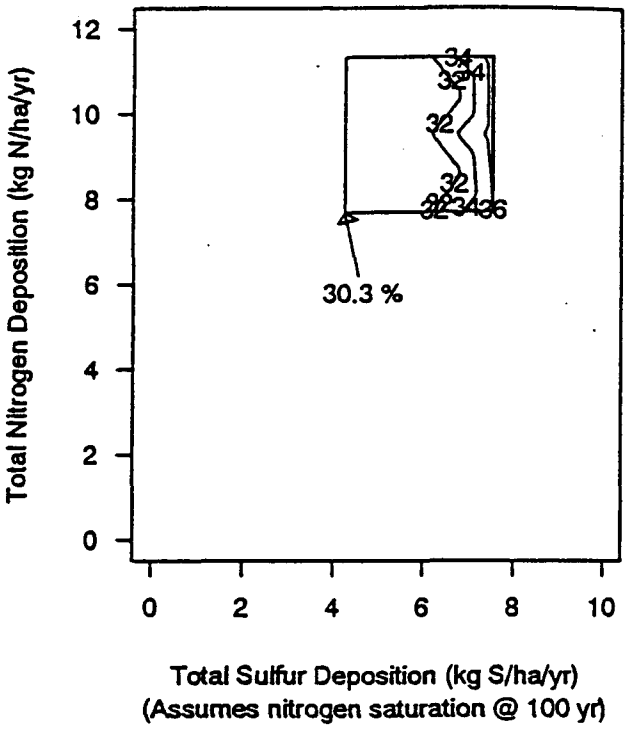


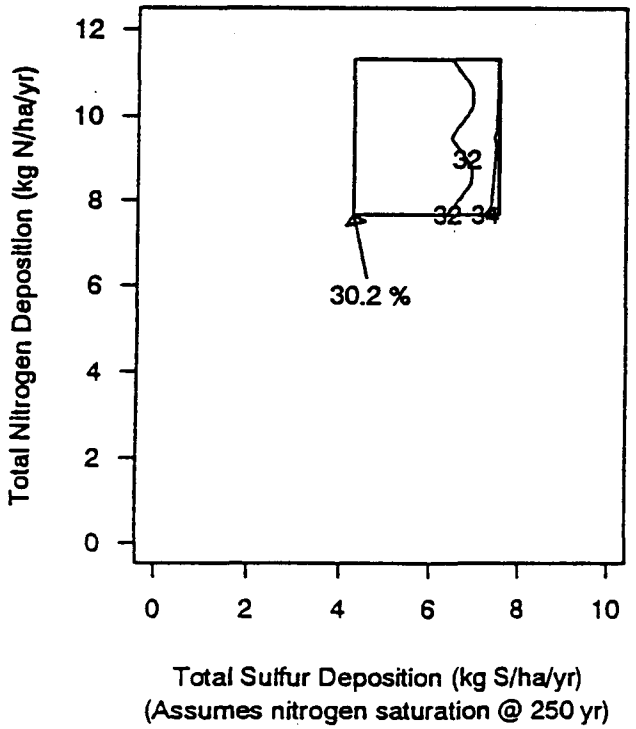


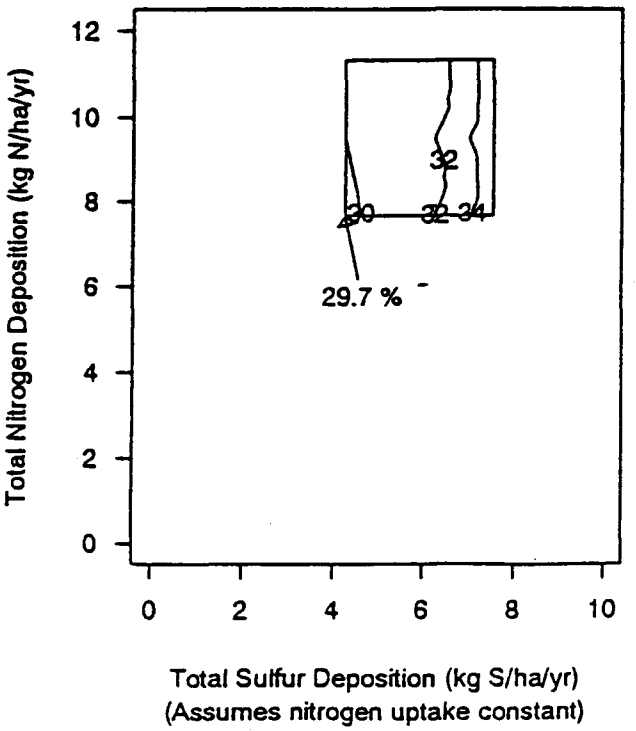


Percent of target population lakes with pH<=6.0,
Adirondacks Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

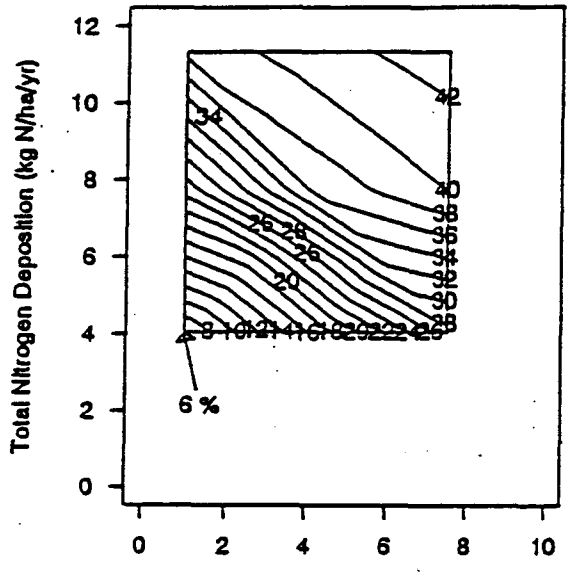


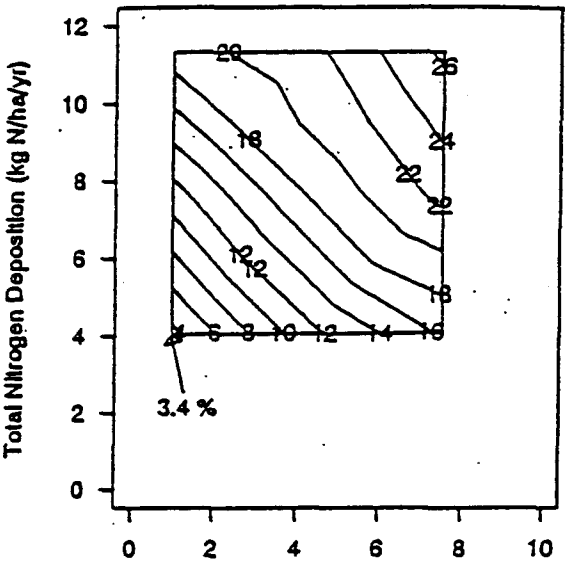


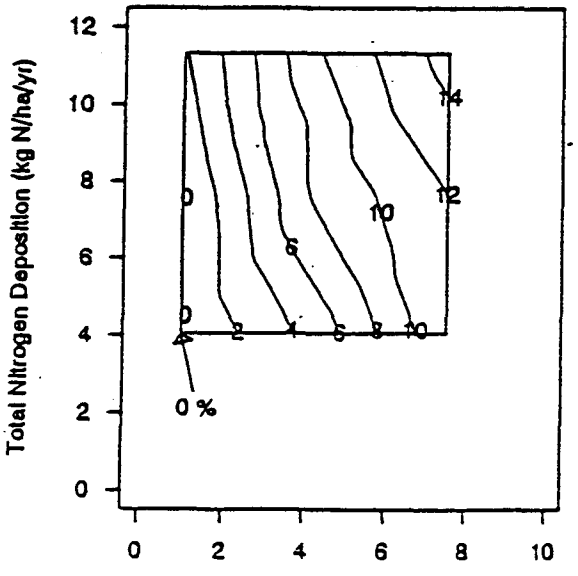


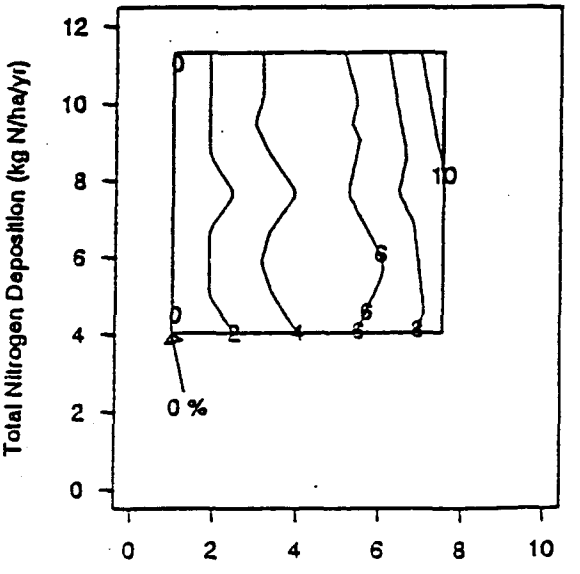


Percent of target population lakes with ANC<=0,
Adirondacks Region at Year 2040
where deposition=median regional @ year 2020.

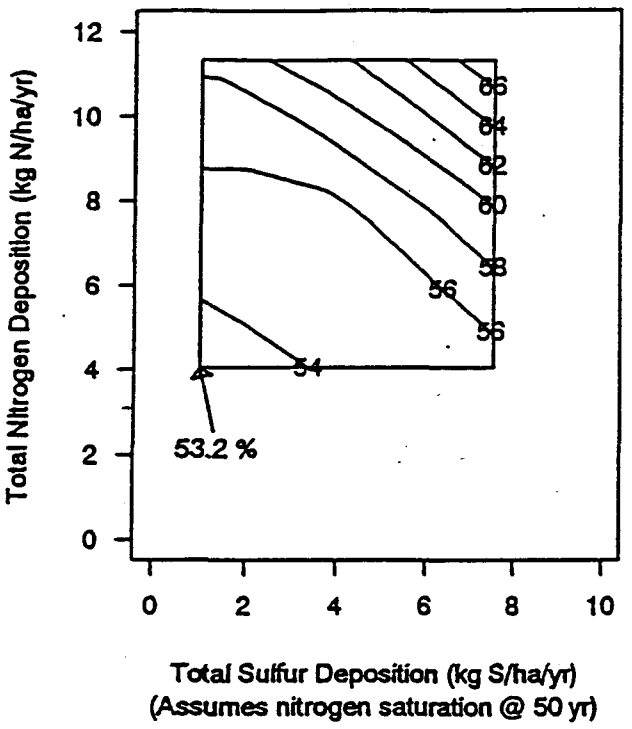


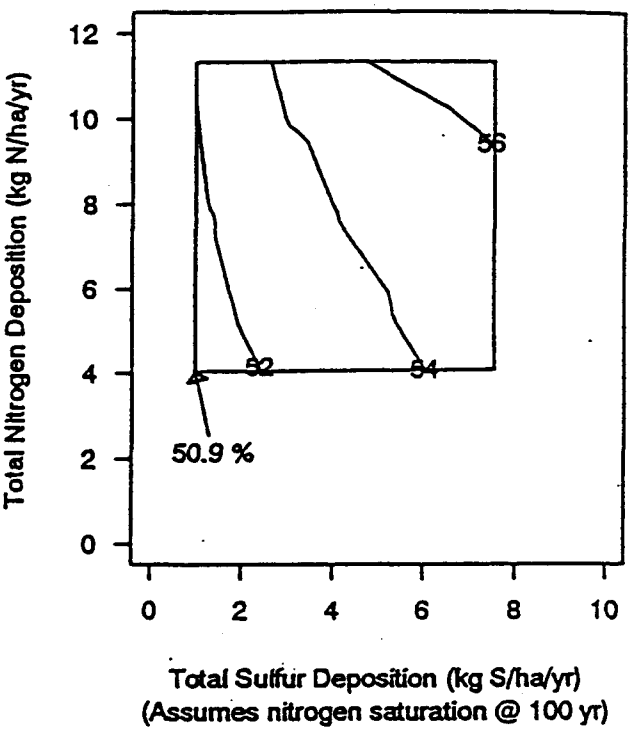


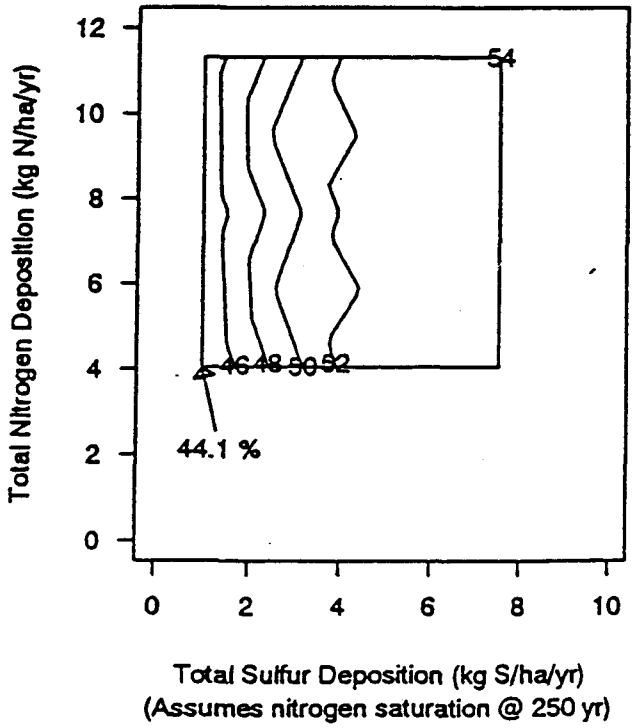


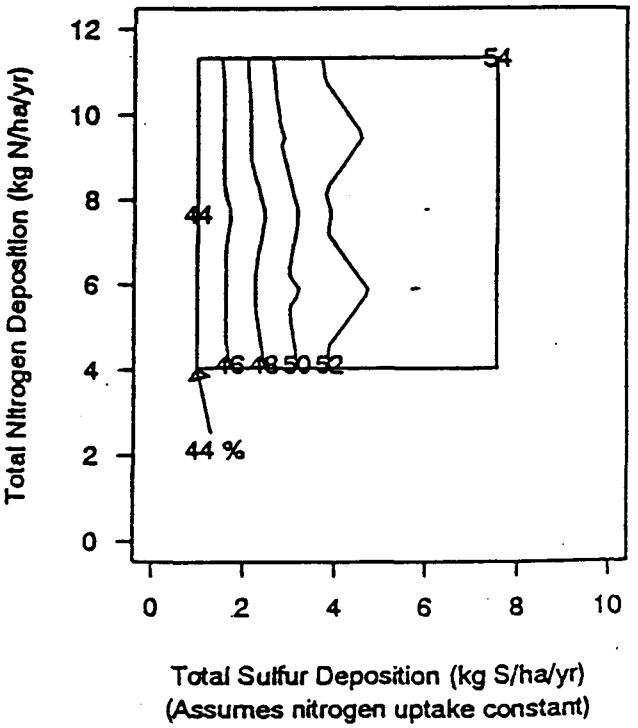


Percent of target population lakes with ANC<=50,
Adirondacks Region at Year 2040
where deposition=median regional @ year 2020.

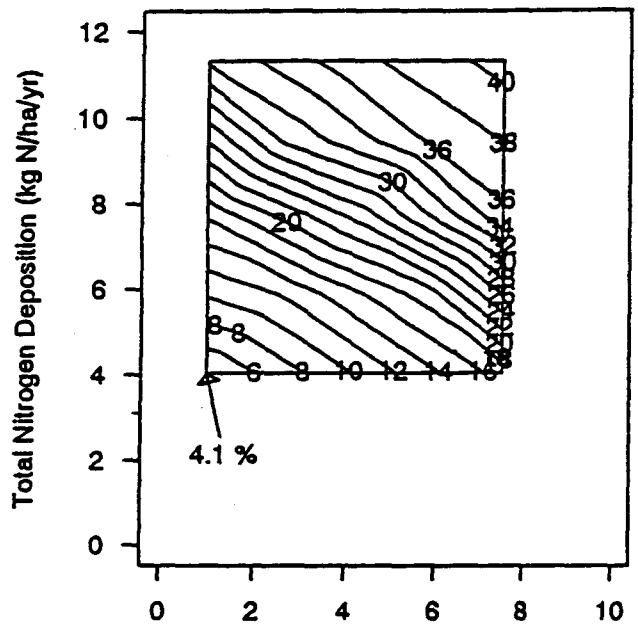


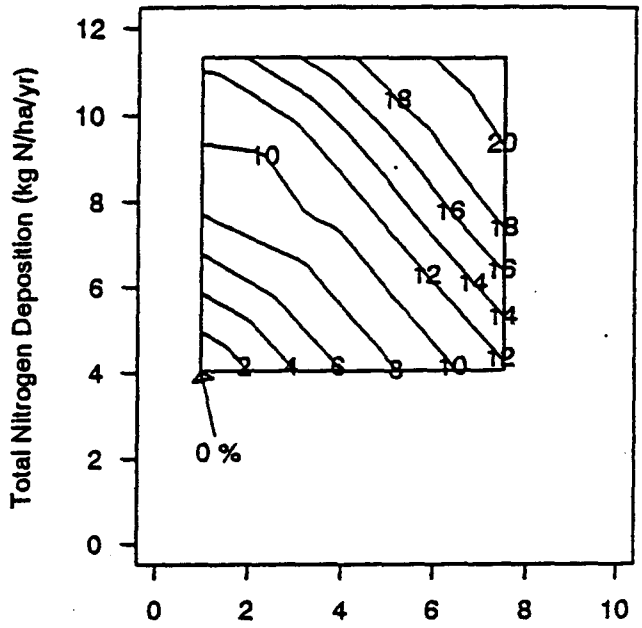


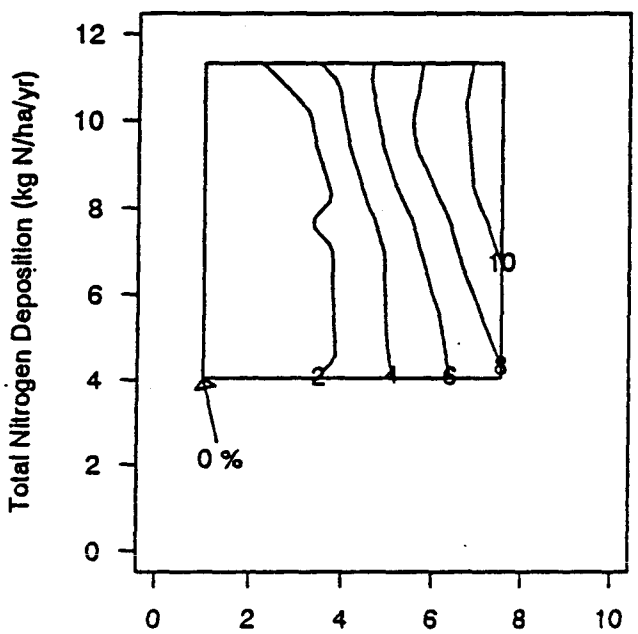


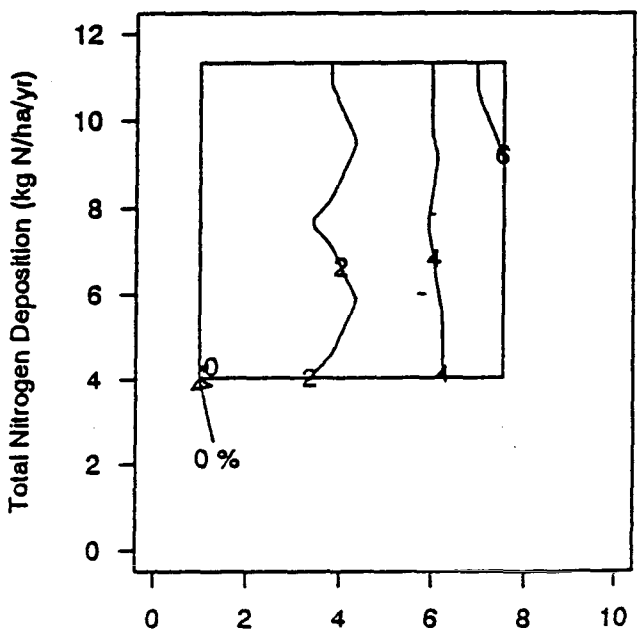


Percent of target population lakes with pH<=5.0,
Adirondacks Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

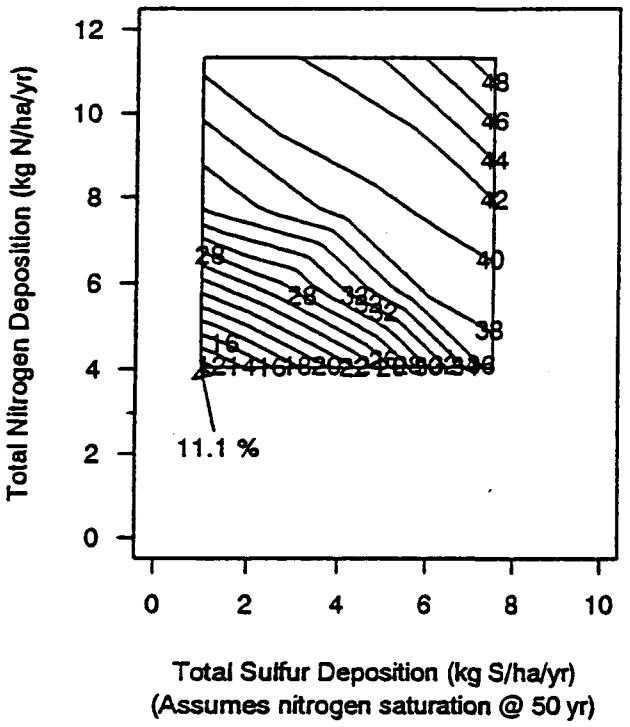


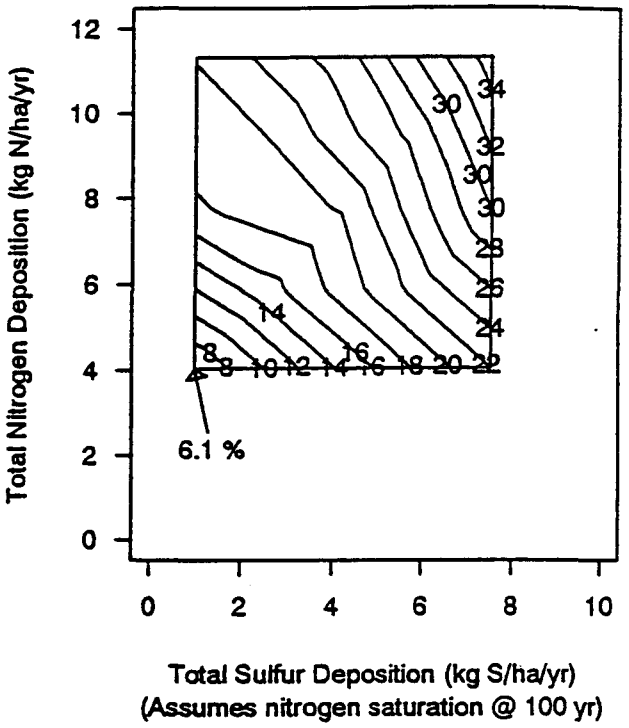


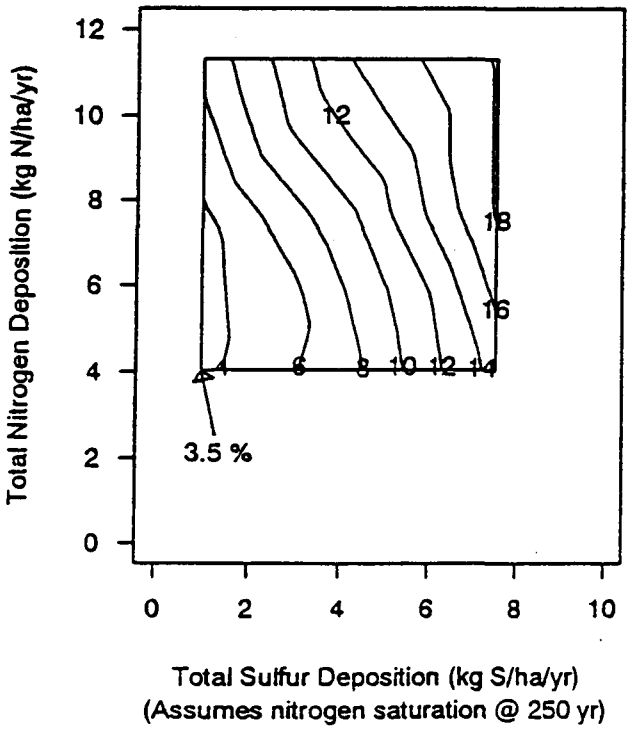


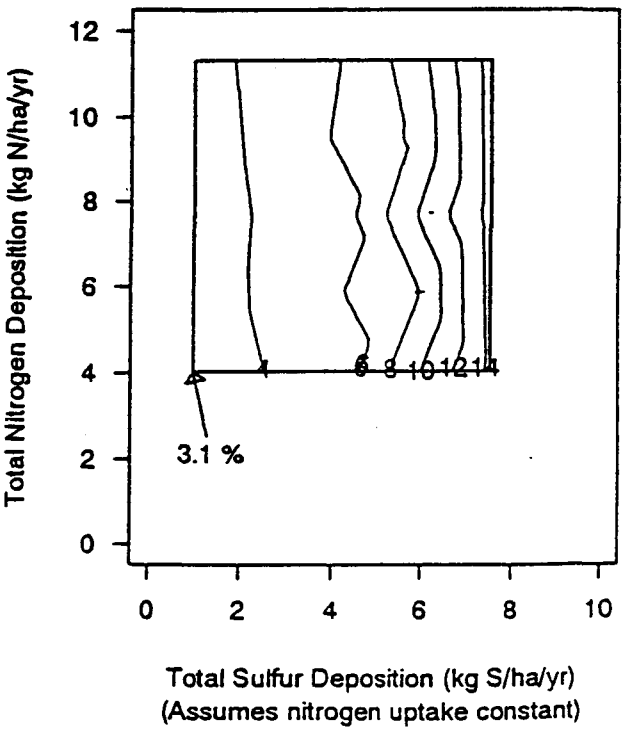


Percent of target population lakes with pH<=5.5,
Adirondacks Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

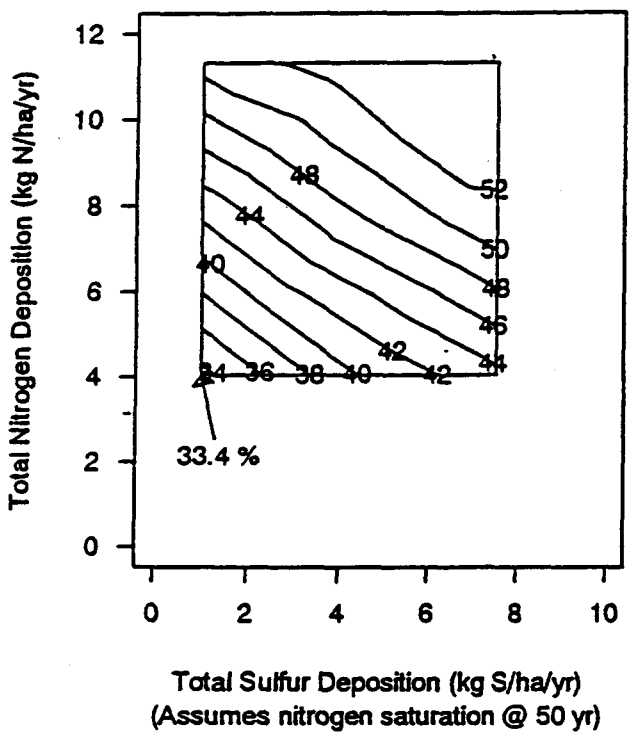


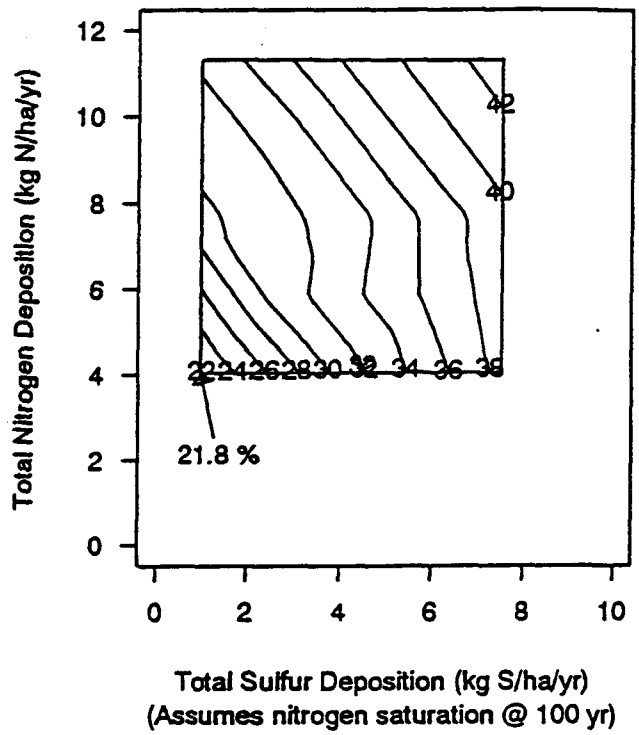


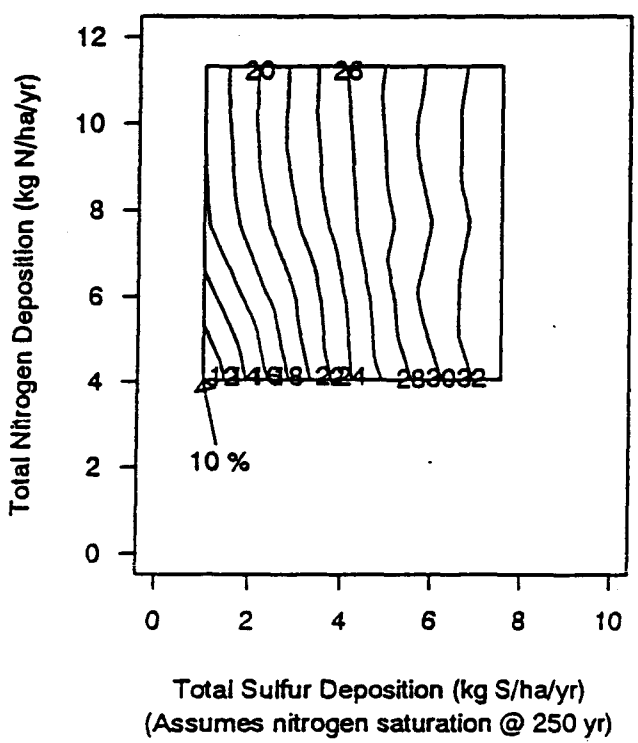


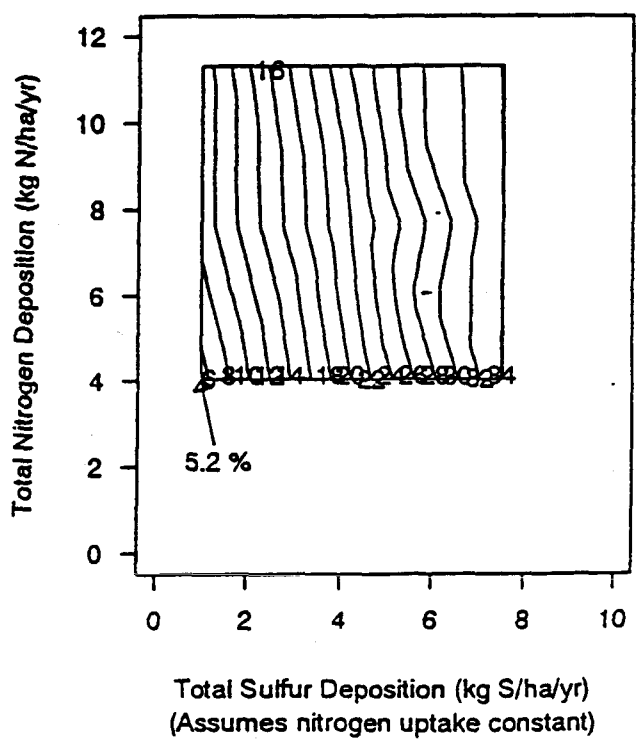


Percent of target population lakes with pH<=6.0,
Adirondacks Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

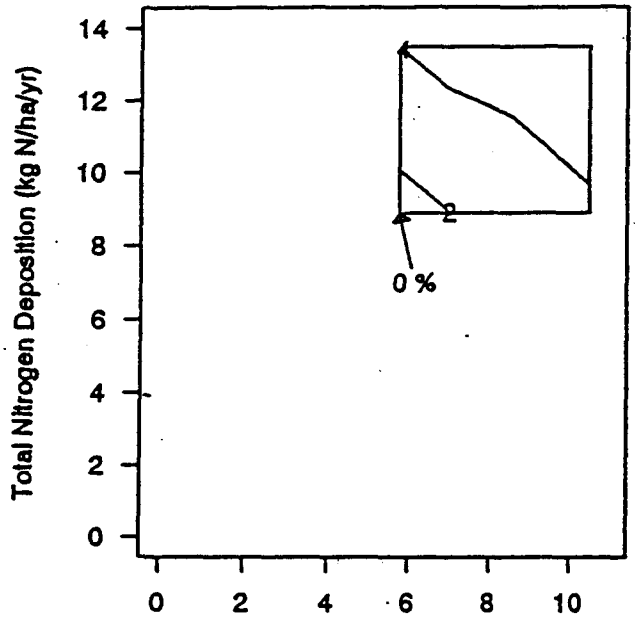


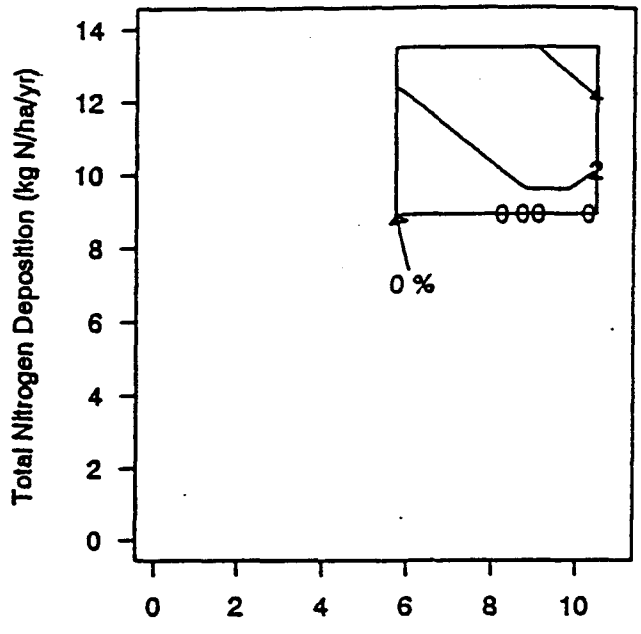


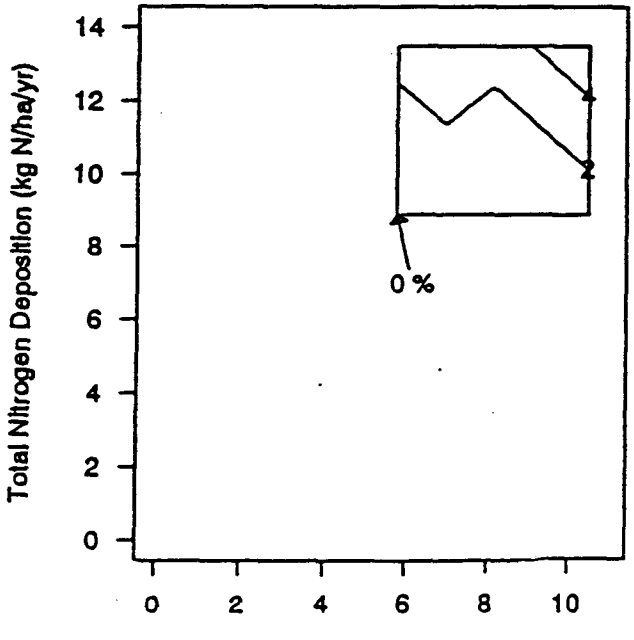


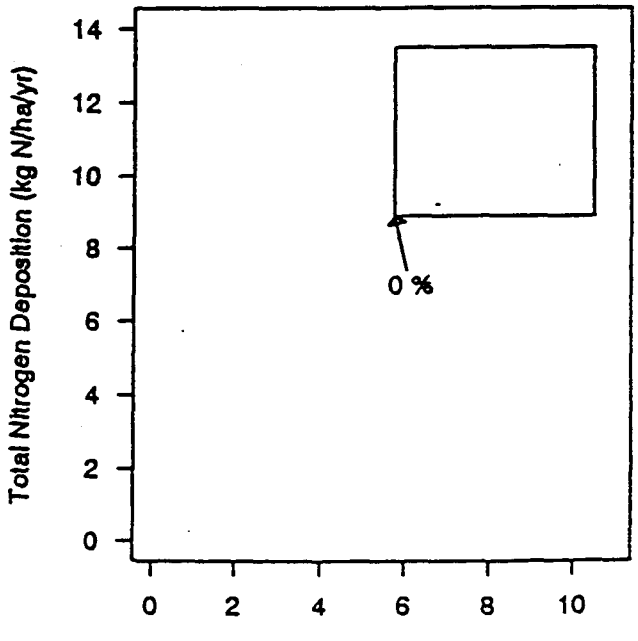


Percent of target population streams with ANC<=0,
Mid-Appalachian Region at Year 2015
where deposition=median regional @ year 2015.

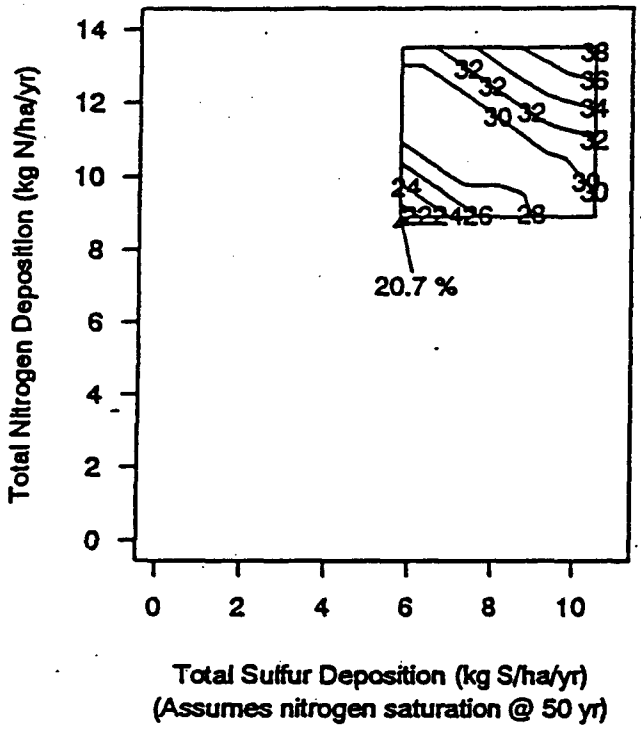


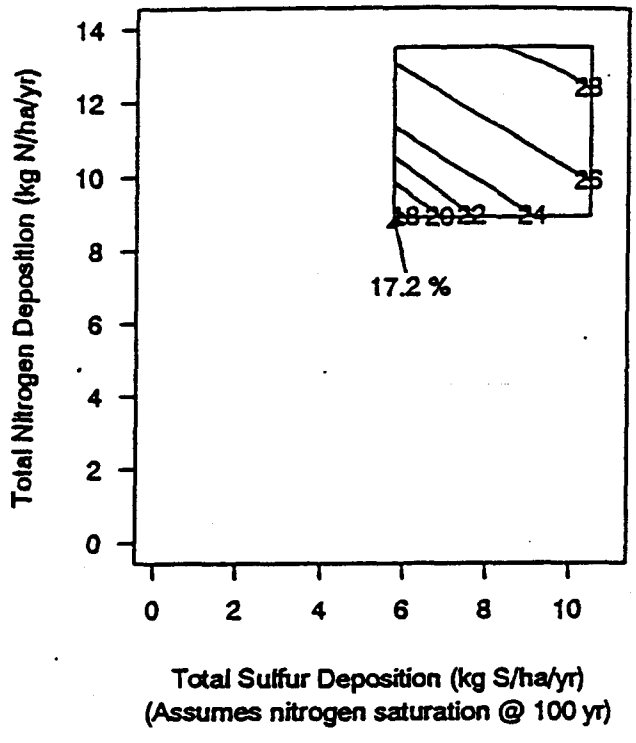


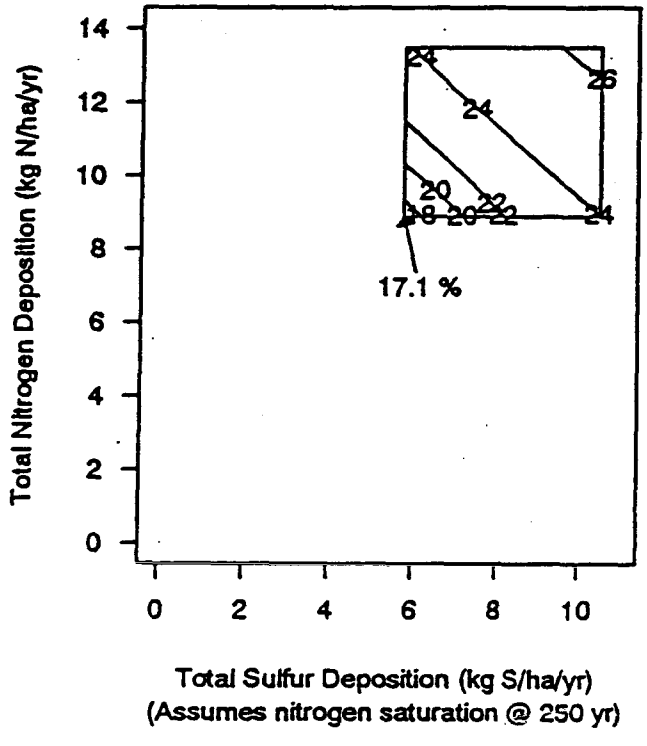


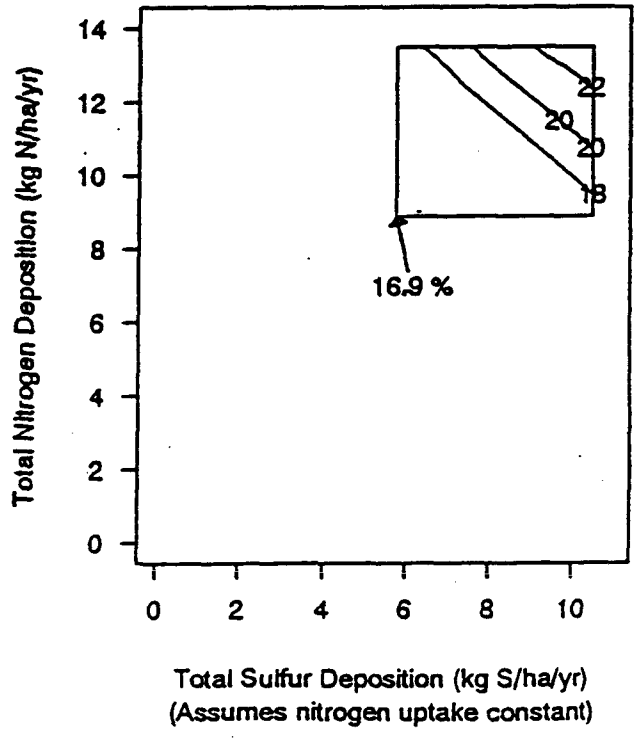


Percent of target population streams with ANC<=50,
Mid-Appalachian Region at Year 2015
where deposition=median regional @ year 2015.

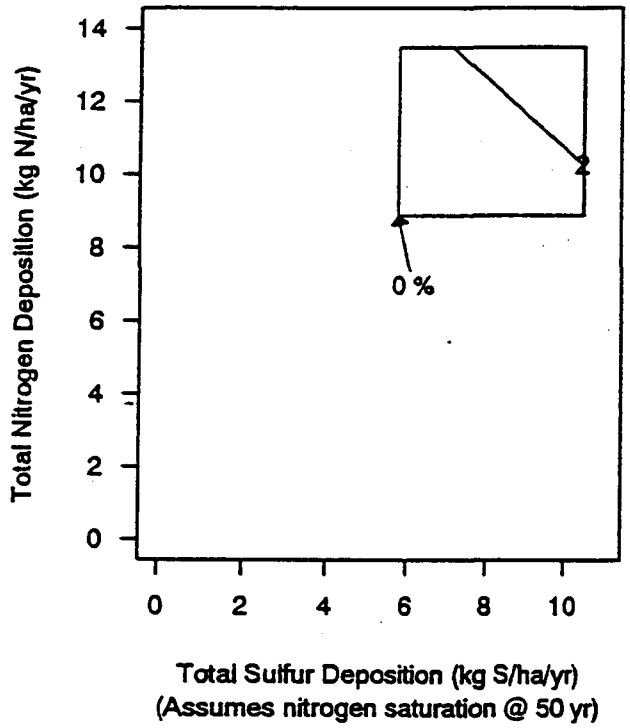


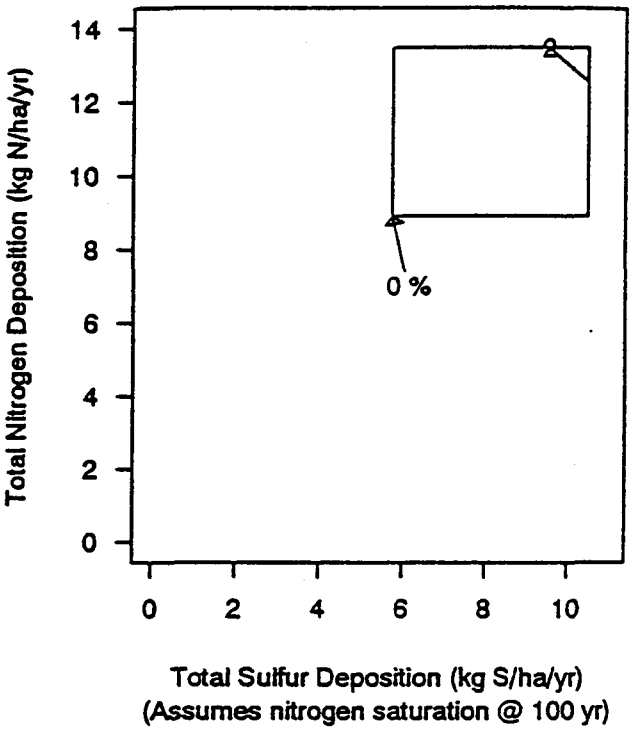


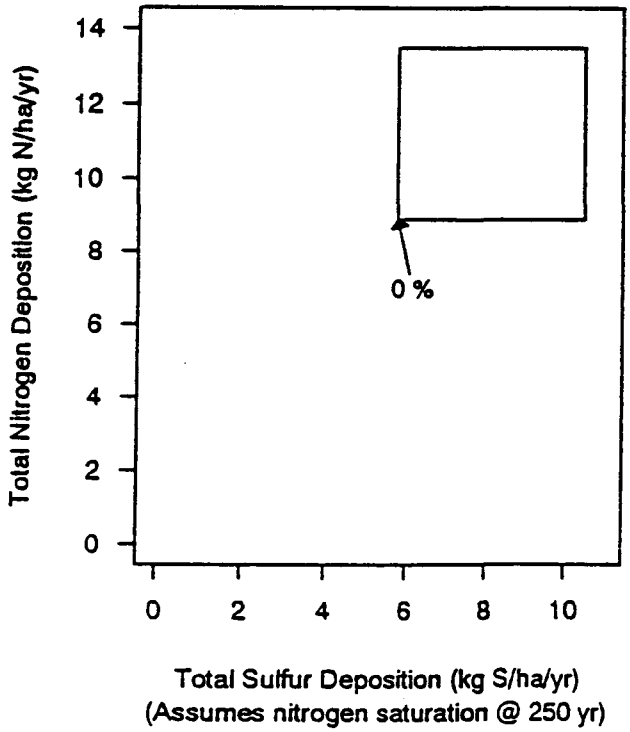


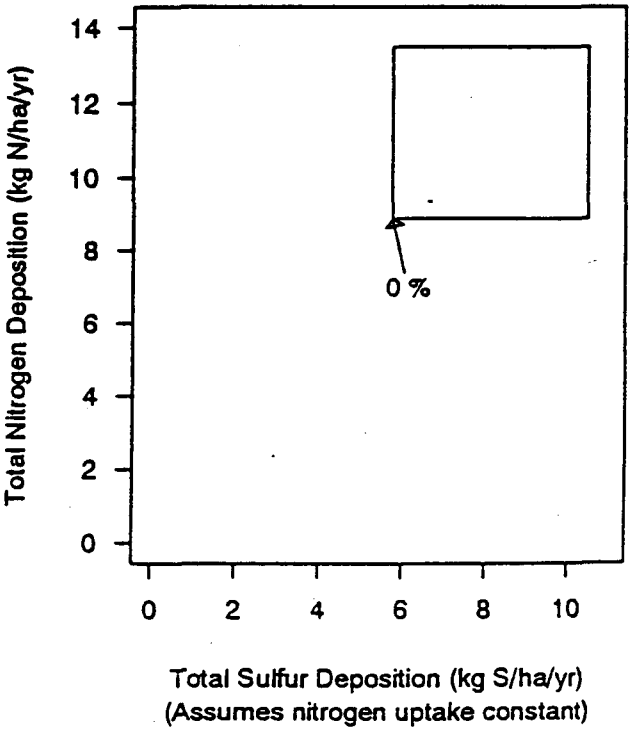


Percent of target population streams with pH<=5.0,
Mid-Appalachian Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

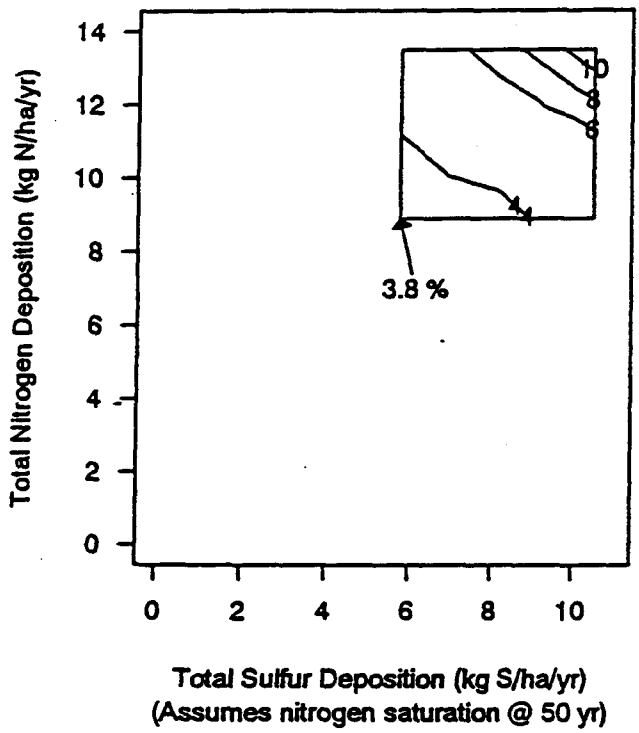


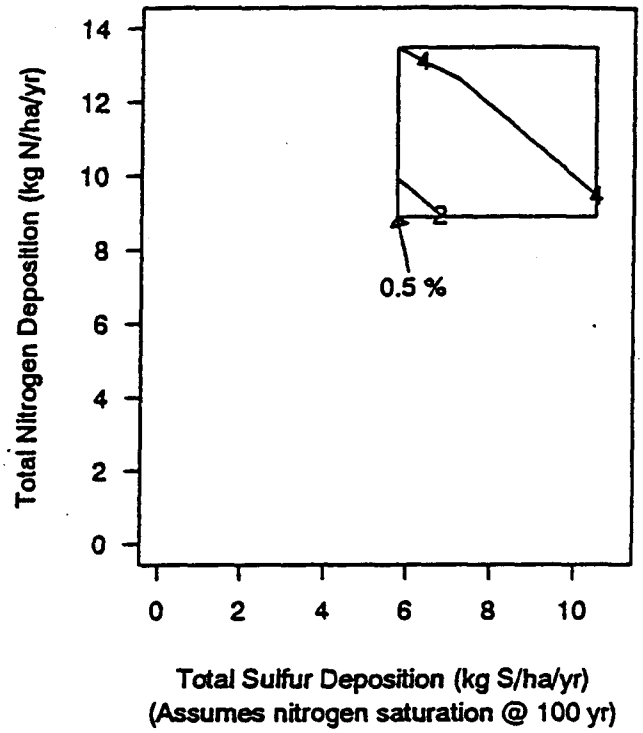


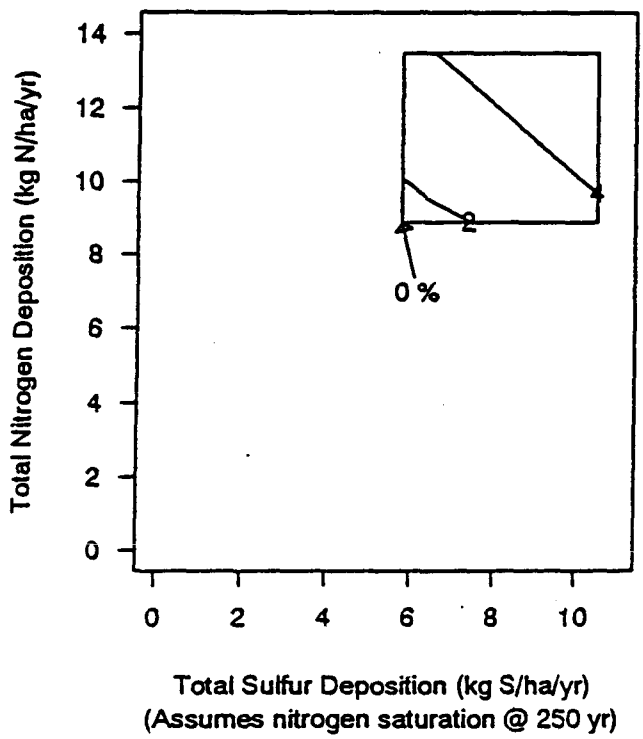


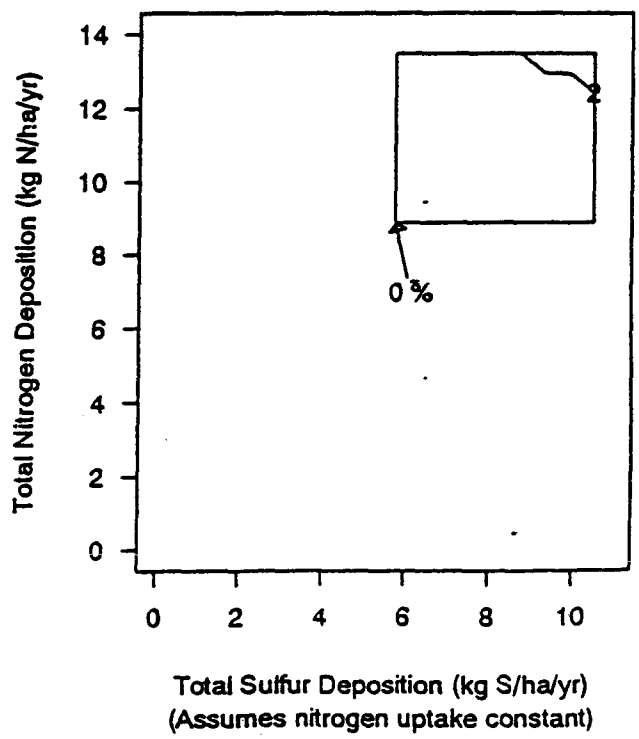


Percent of target population streams with pH<=5.5,
Mid-Appalachian Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

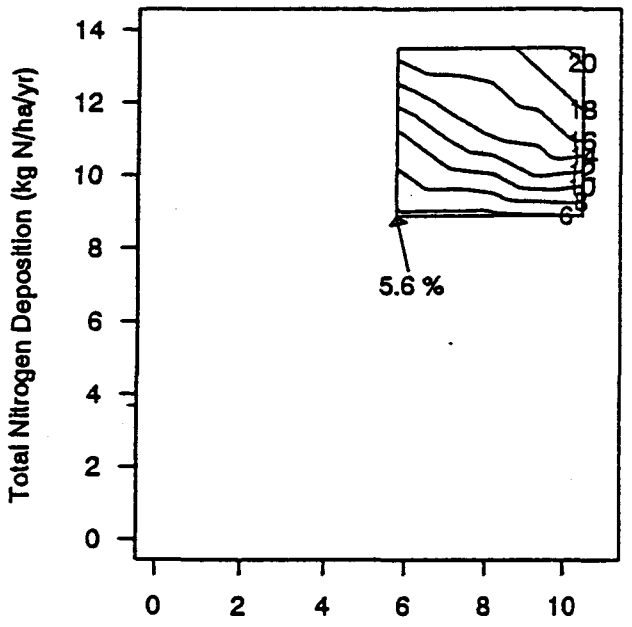


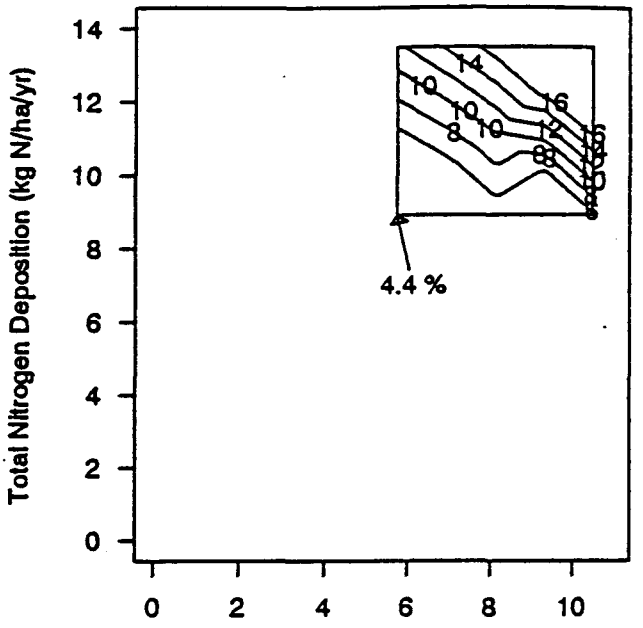


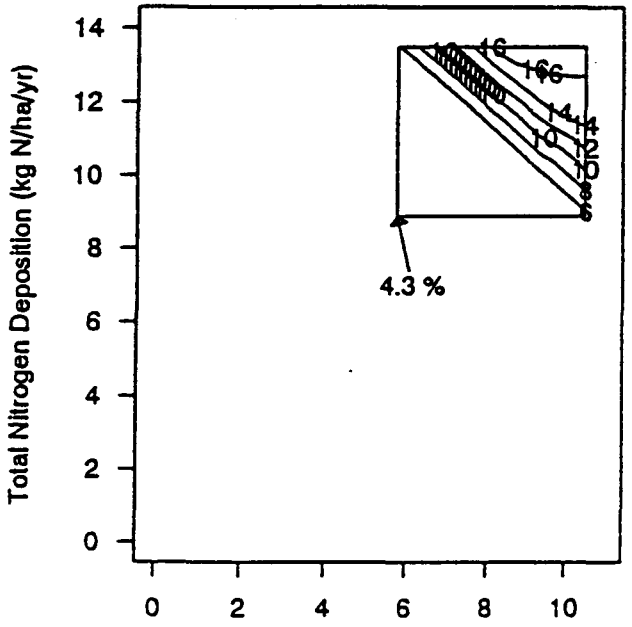


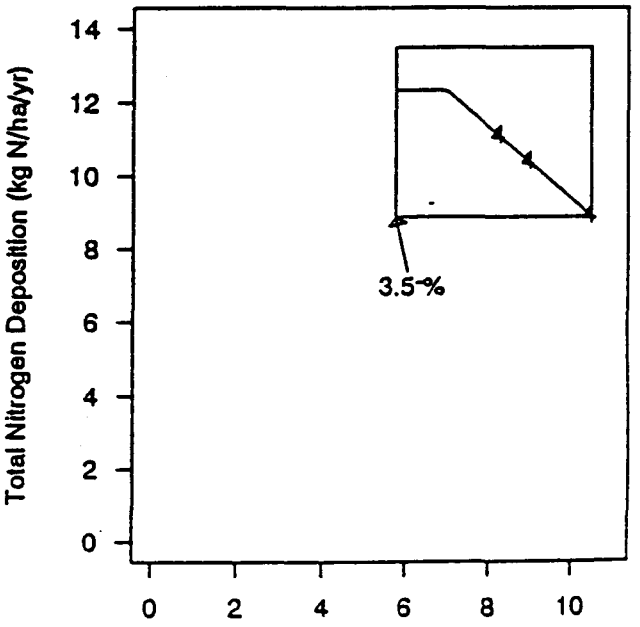


Percent of target population streams with pH<=6.0,
Mid-Appalachian Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

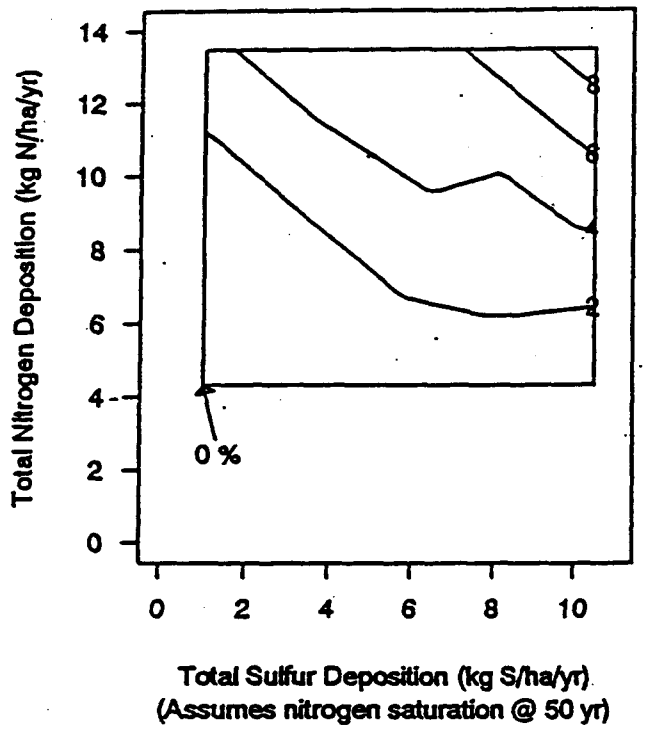


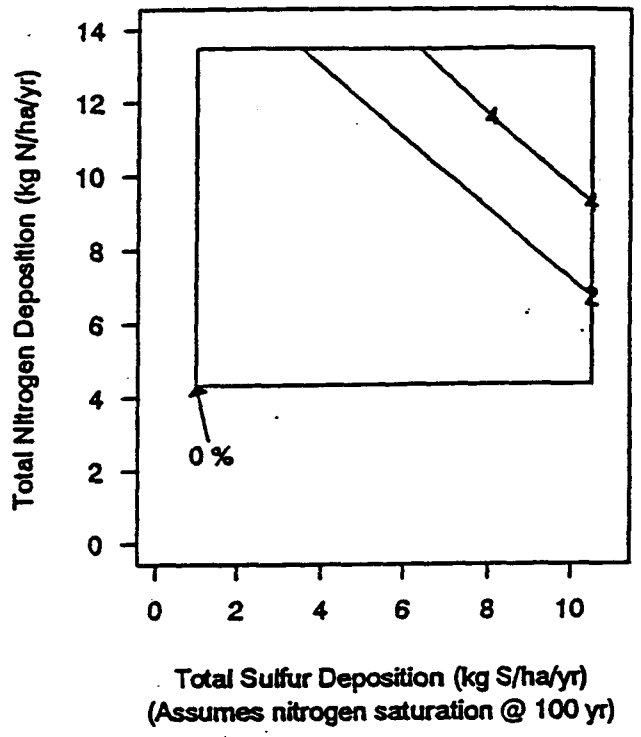


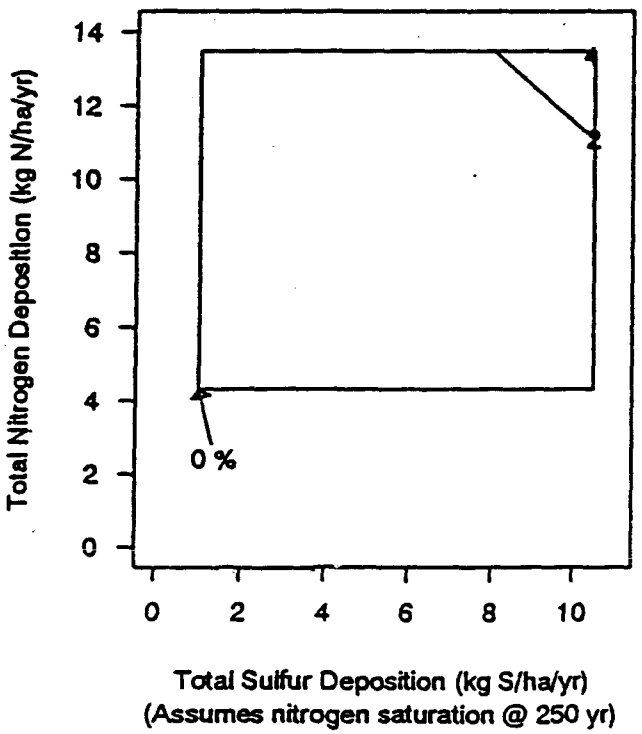


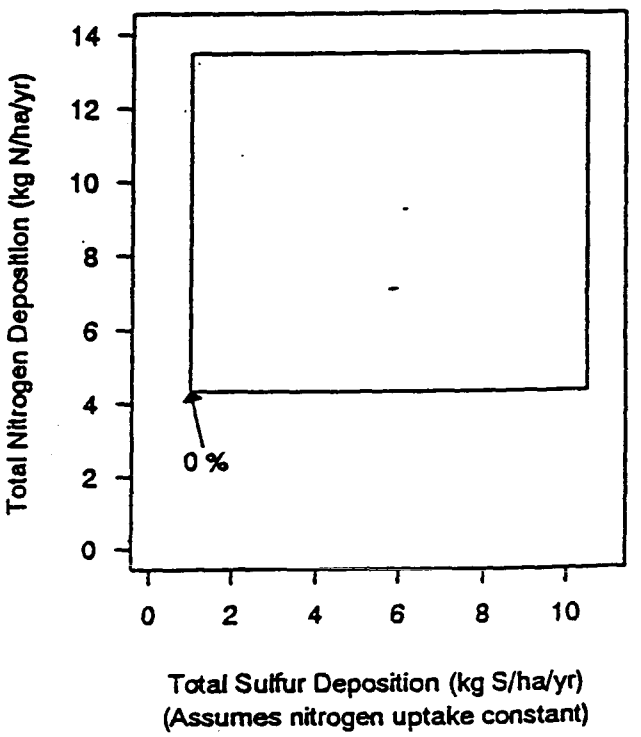


Percent of target population streams with ANC<=0, Mid-Appalachian Region at Year 2040 where deposition=median regional @ year 2020.

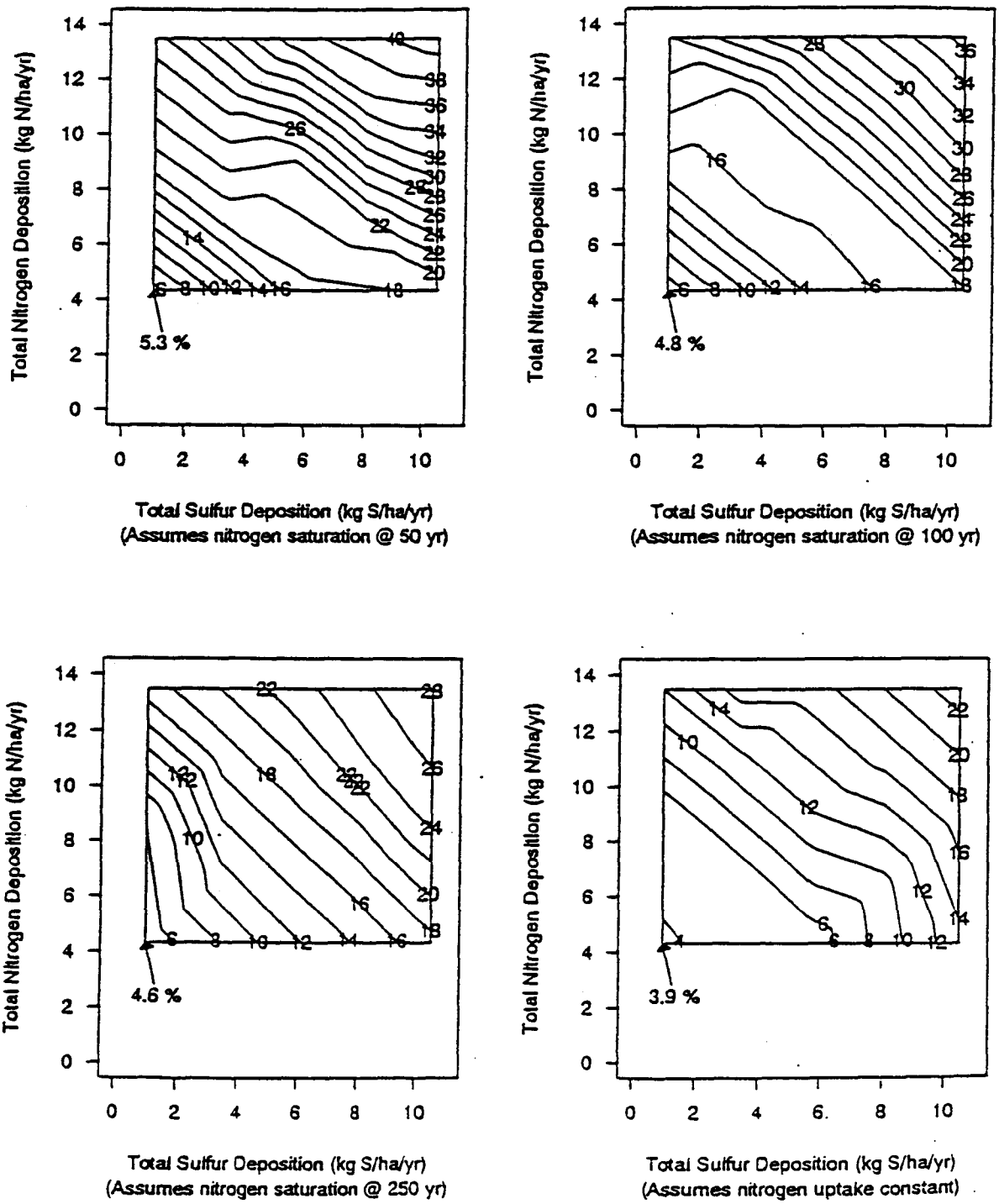




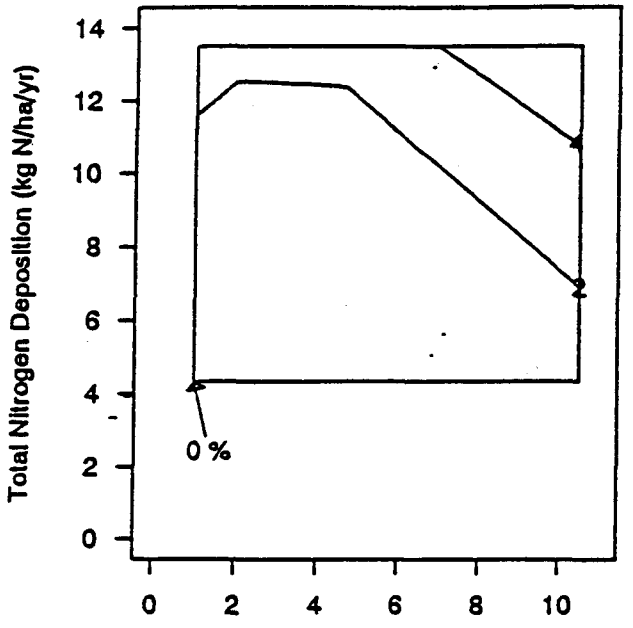


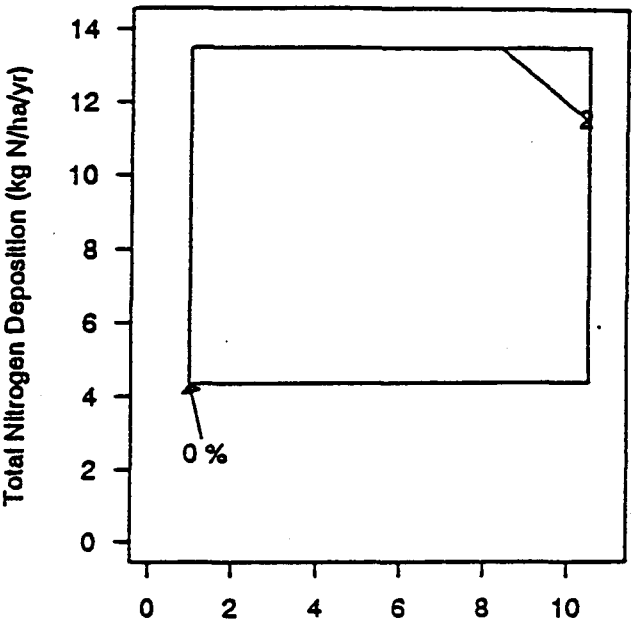


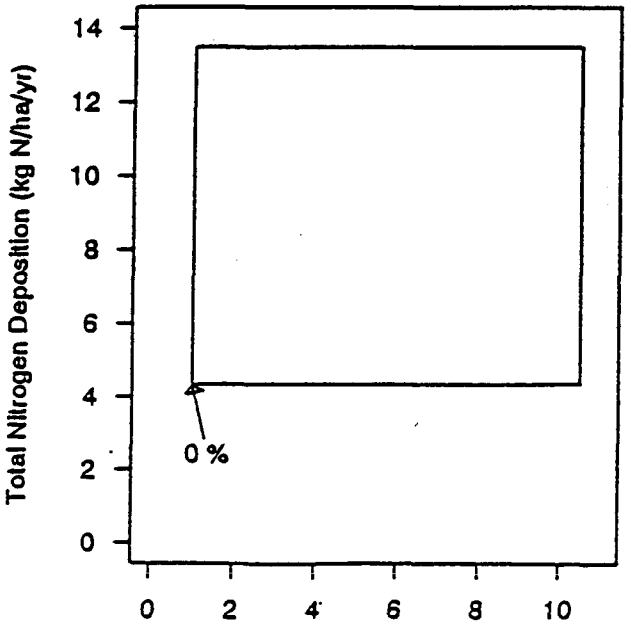
Percent of target population streams with ANC<=50,
Mid-Appalachian Region at Year 2040
where deposition=median regional @ year 2020.

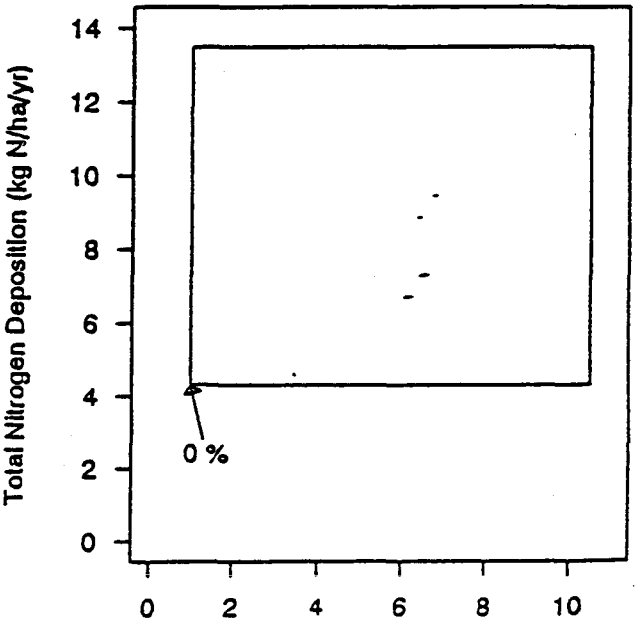


Percent of target population streams with pH<=5.0,
Mid-Appalachian Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

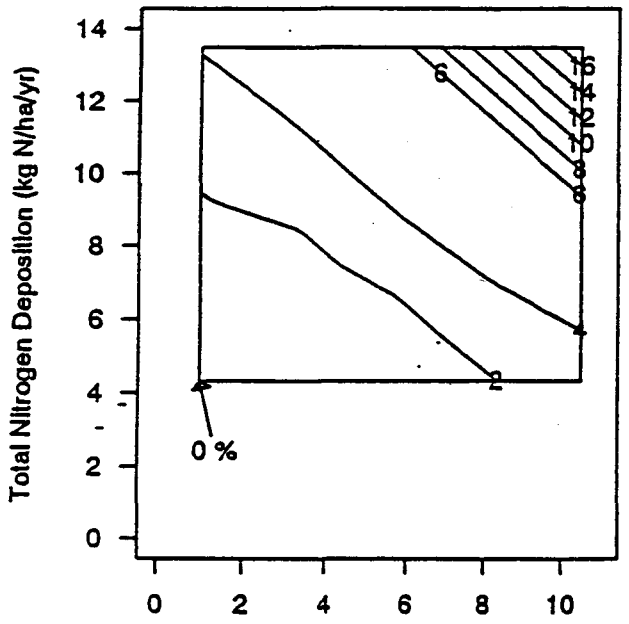


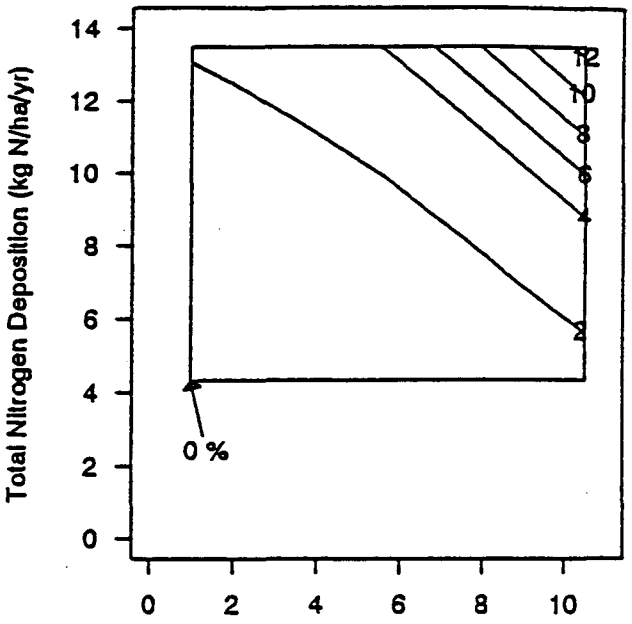


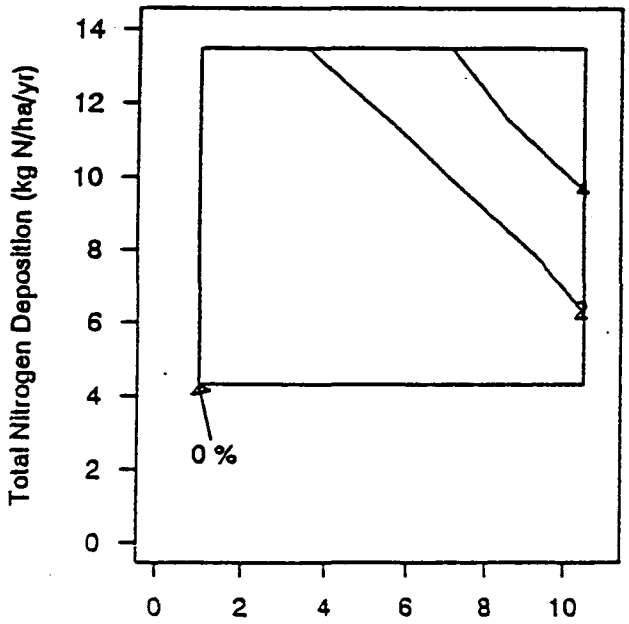


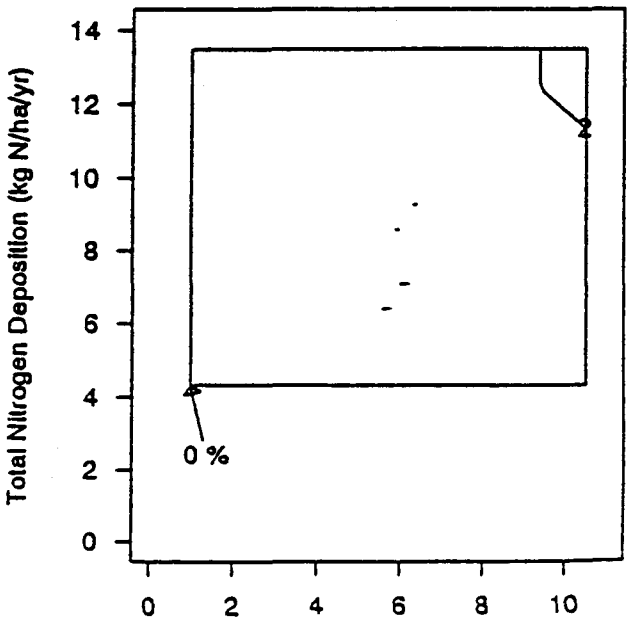


Percent of target population streams with pH<=5.5,
Mid-Appalachian Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

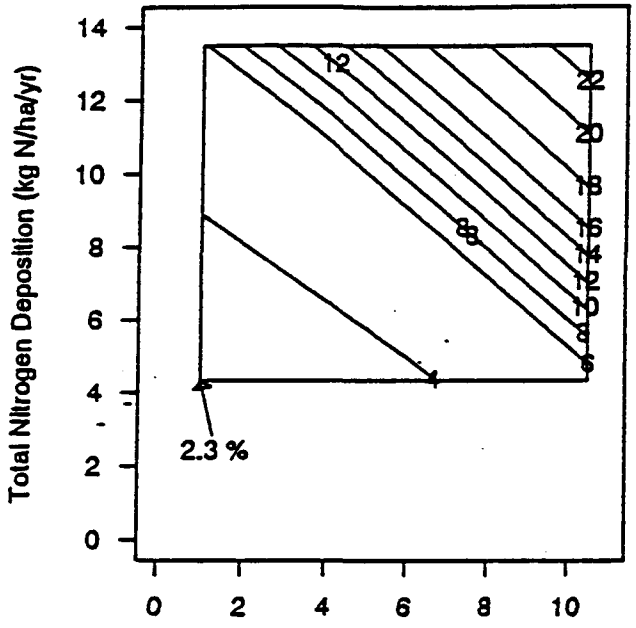


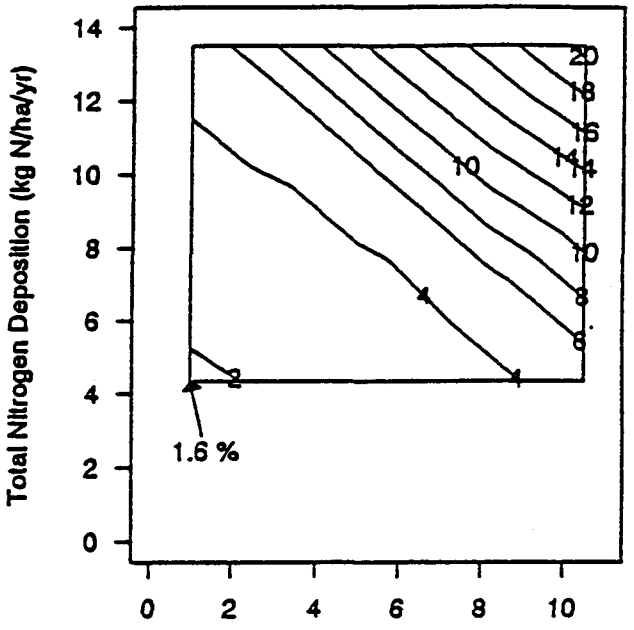


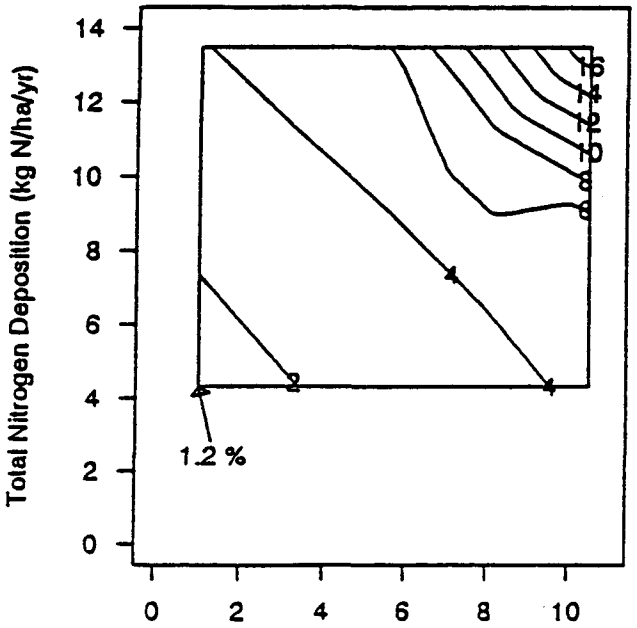


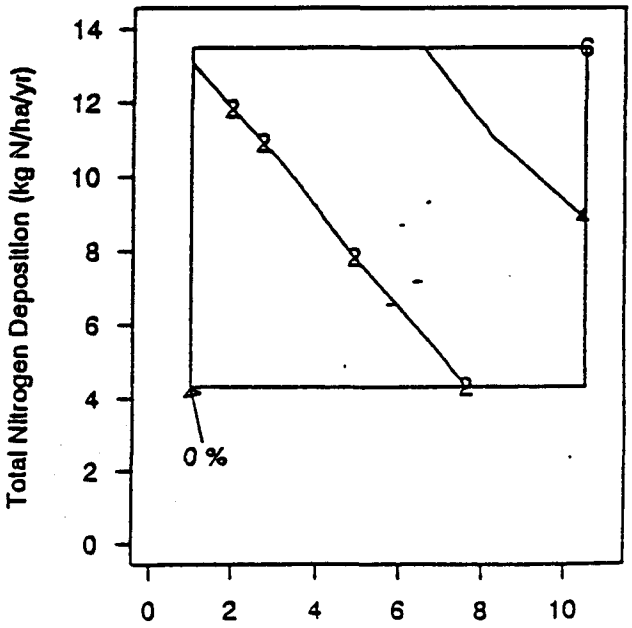


Percent of target population streams with pH<=6.0,
Mid-Appalachian Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

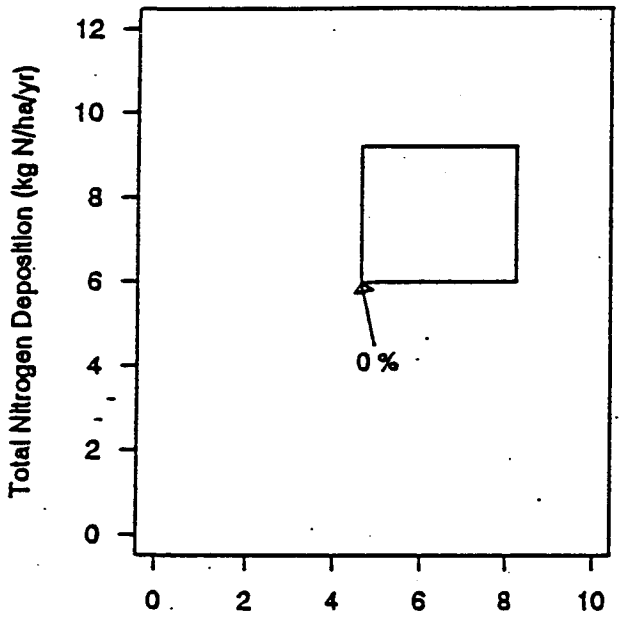




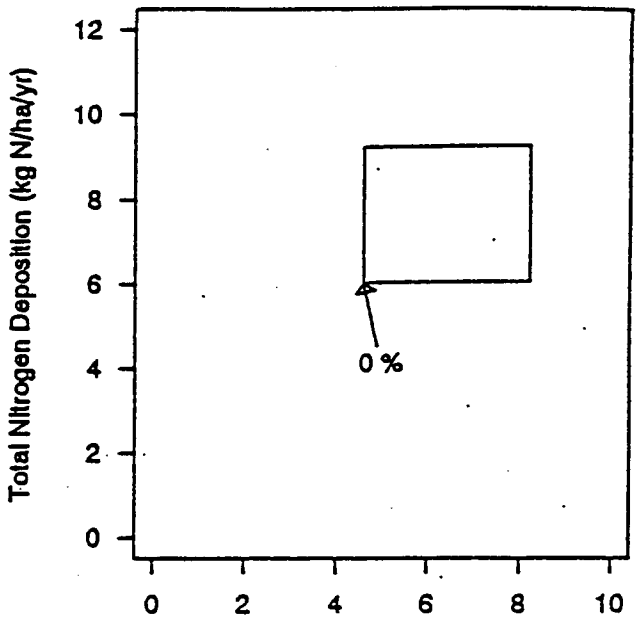




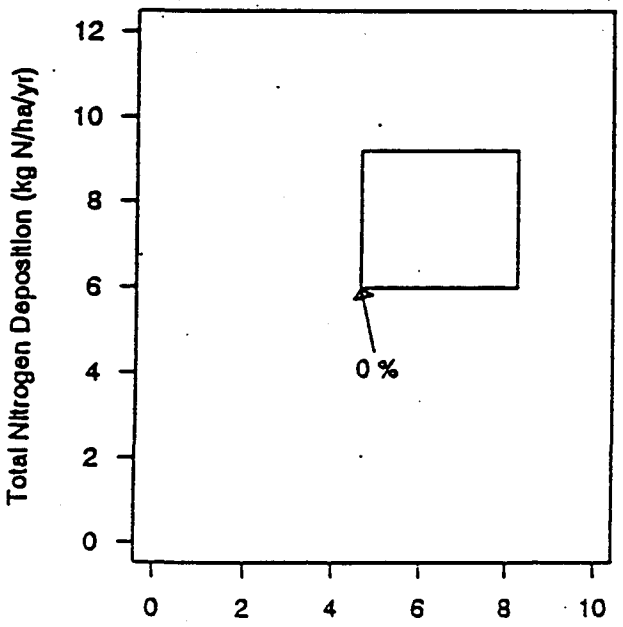
Percent of target population streams with ANC<=0,
Southern Blue Ridge Region at Year 2015
where deposition=median regional @ year 2015.



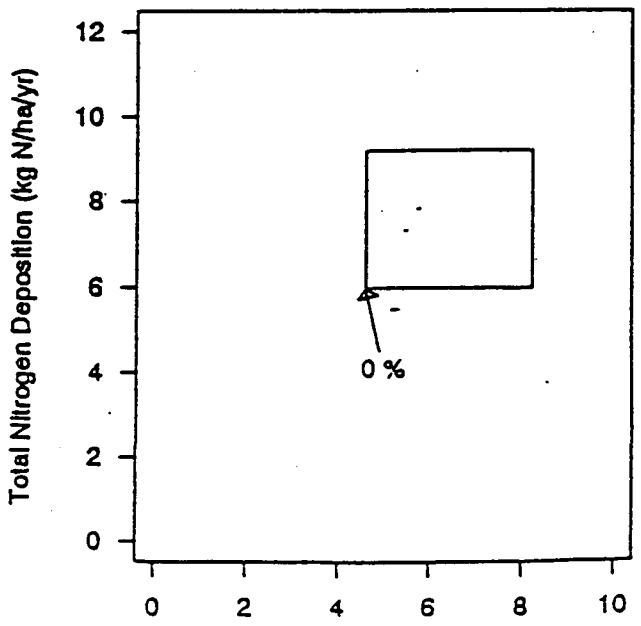
Total Sulfur Deposition (kg S/ha/yr)
(Assumes nitrogen saturation @ 50 yr)



Total Sulfur Deposition (kg S/ha/yr)
(Assumes nitrogen saturation @ 100 yr)

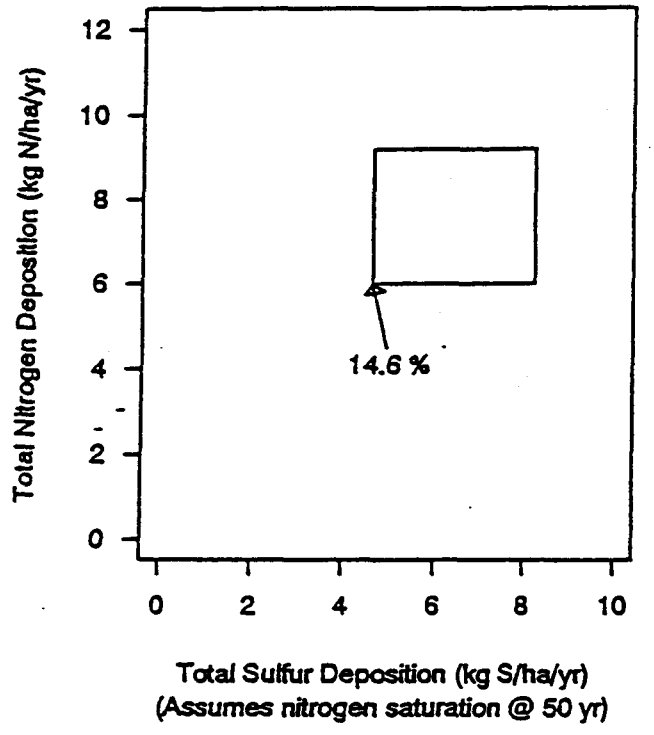


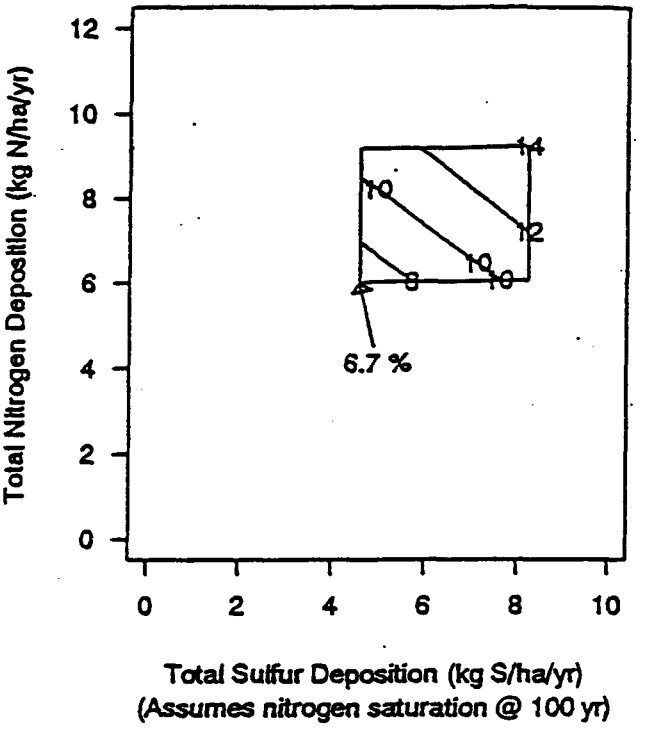
Total Sulfur Deposition (kg S/ha/yr)
(Assumes nitrogen saturation @ 250 yr)

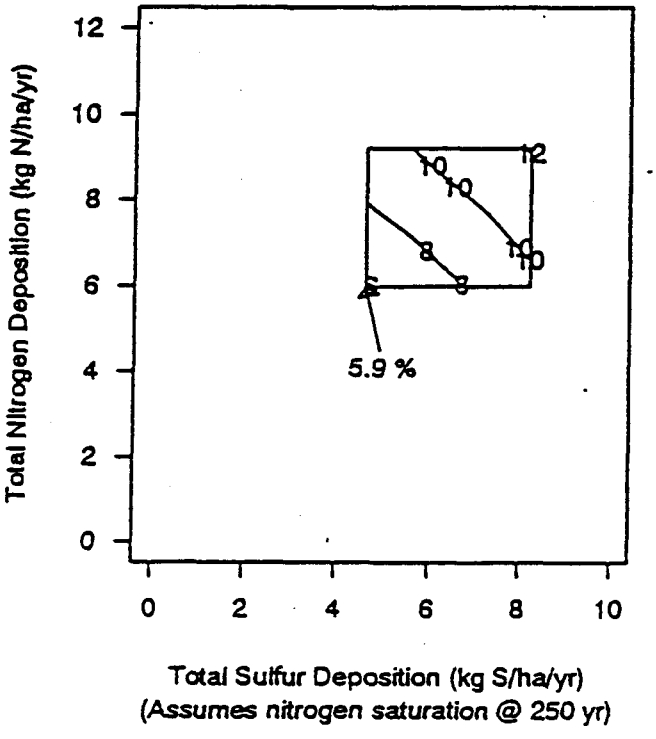


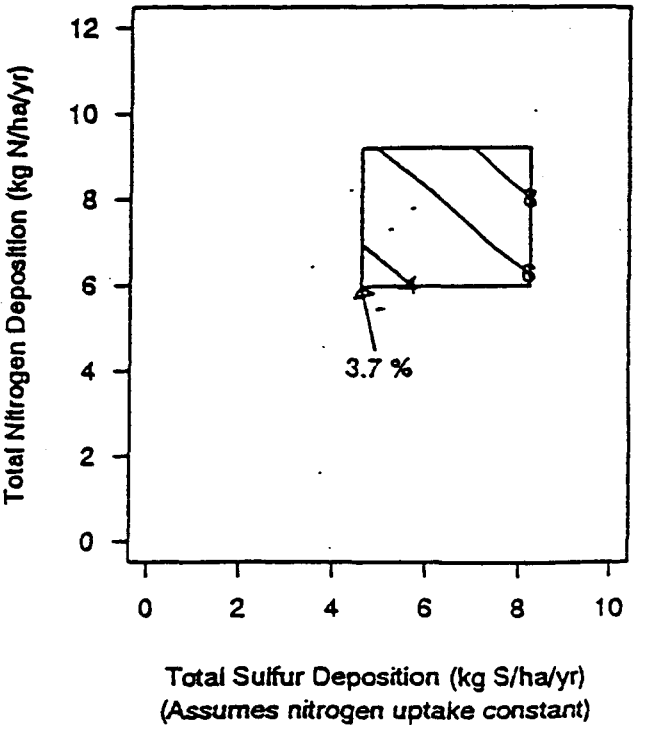
Total Sulfur Deposition (kg S/ha/yr)
(Assumes nitrogen uptake constant)

Percent of target population streams with ANC<=50,
Southern Blue Ridge Region at Year 2015
where deposition=median regional @ year 2015.

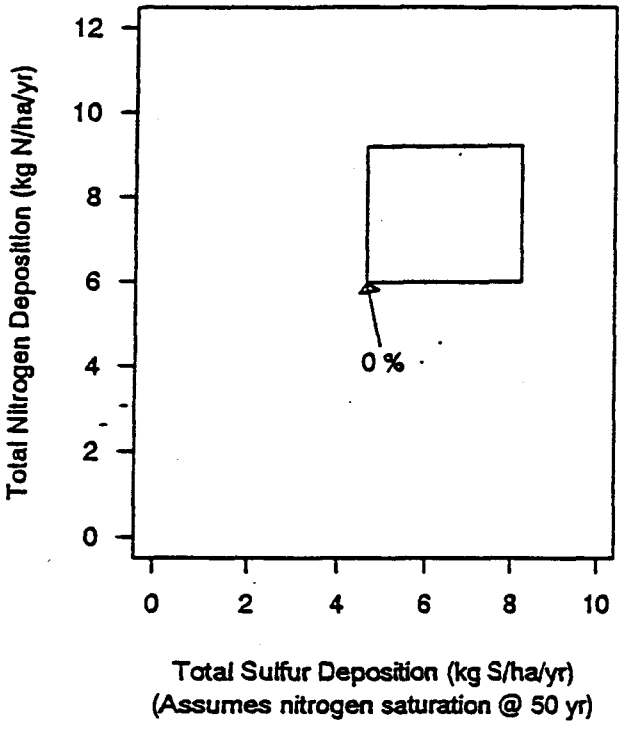


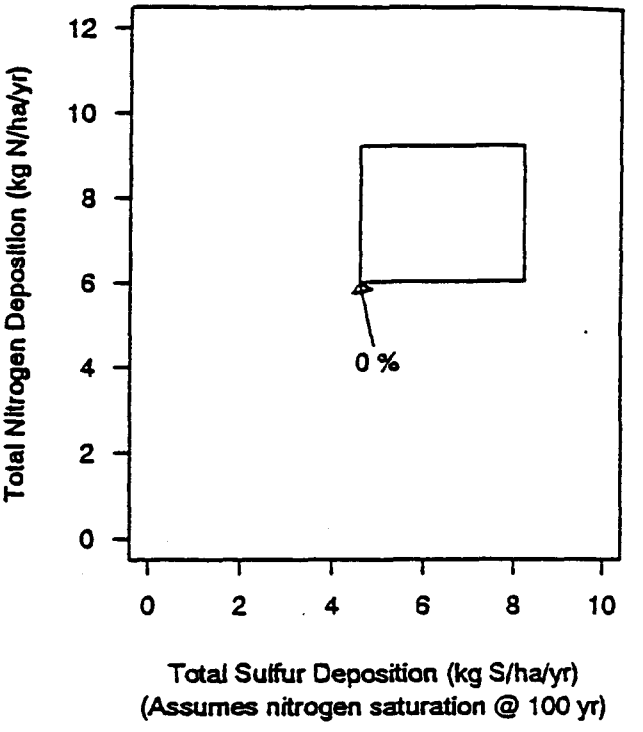


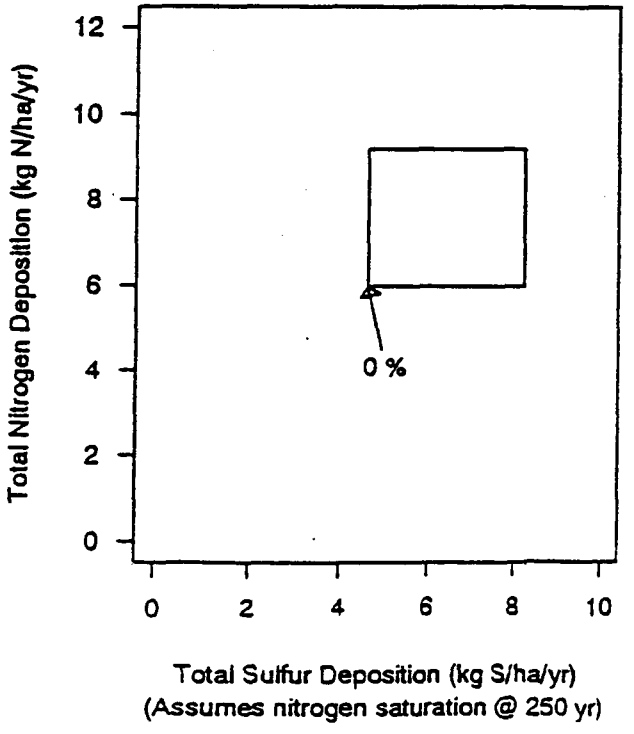


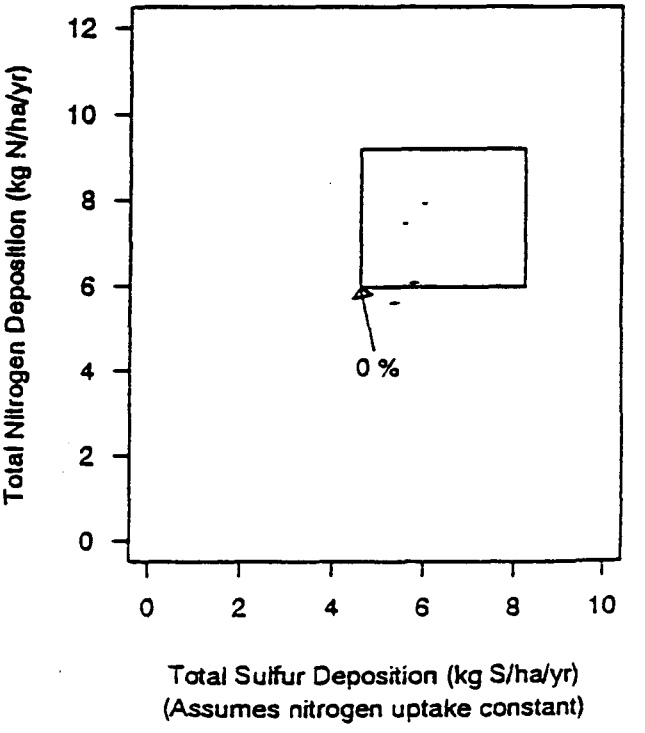


Percent of target population streams with pH<=5.0,
Southern Blue Ridge Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

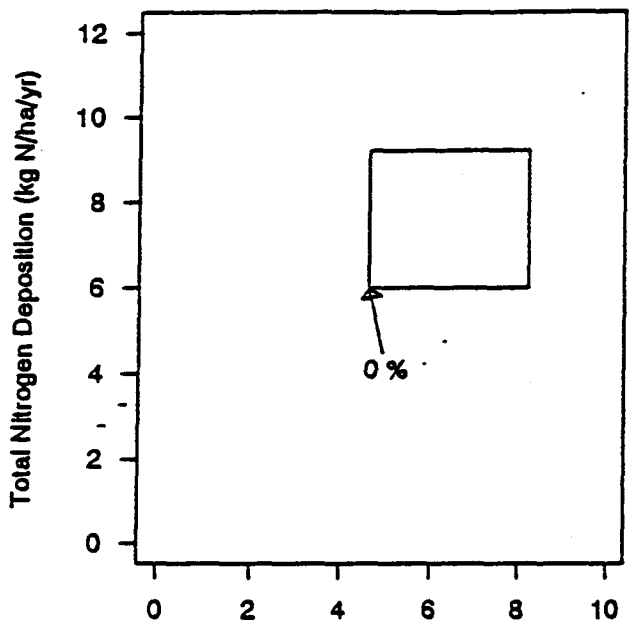


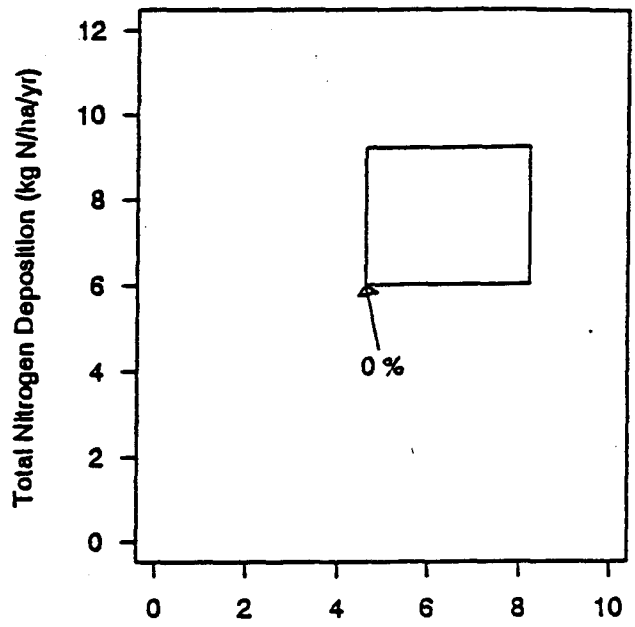


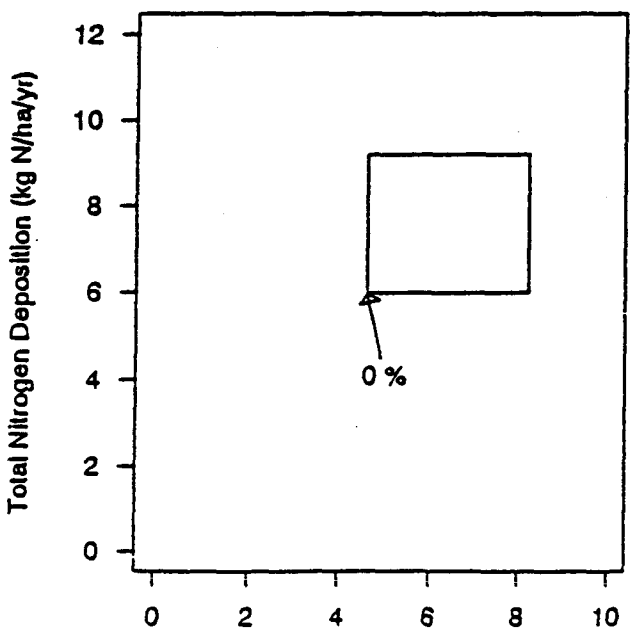


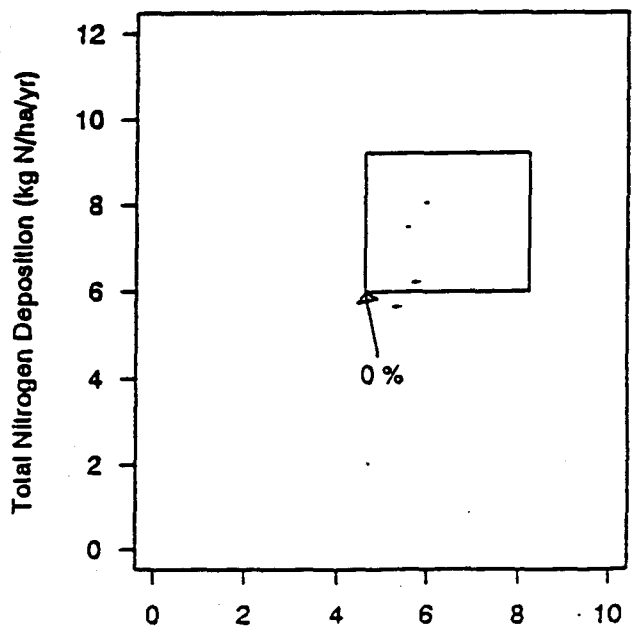


Percent of target population streams with pH<=5.5,
Southern Blue Ridge Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

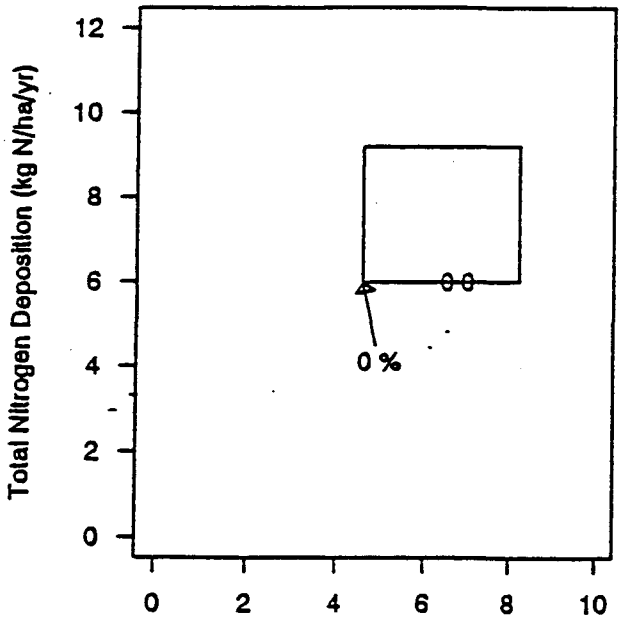


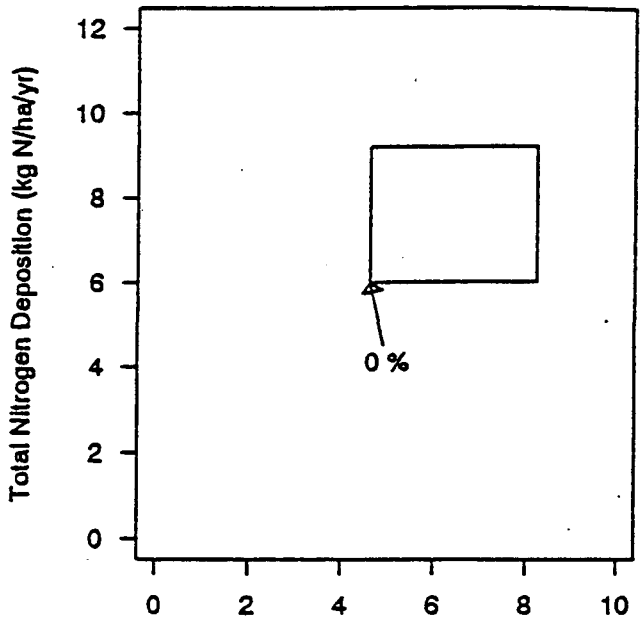


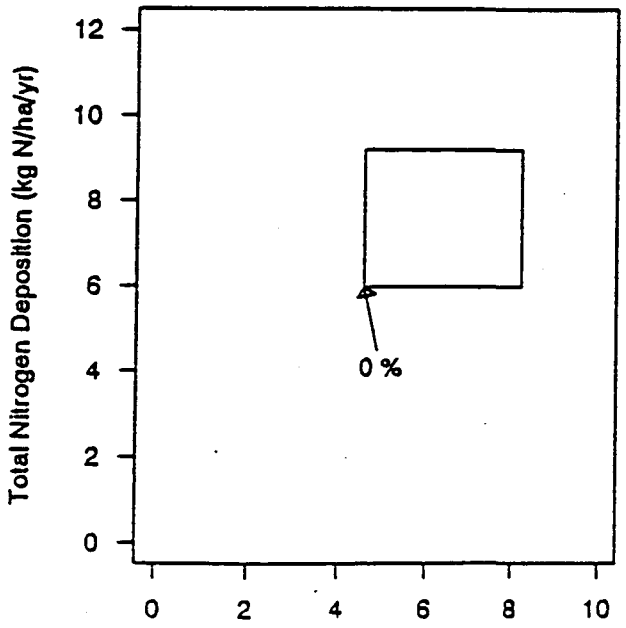


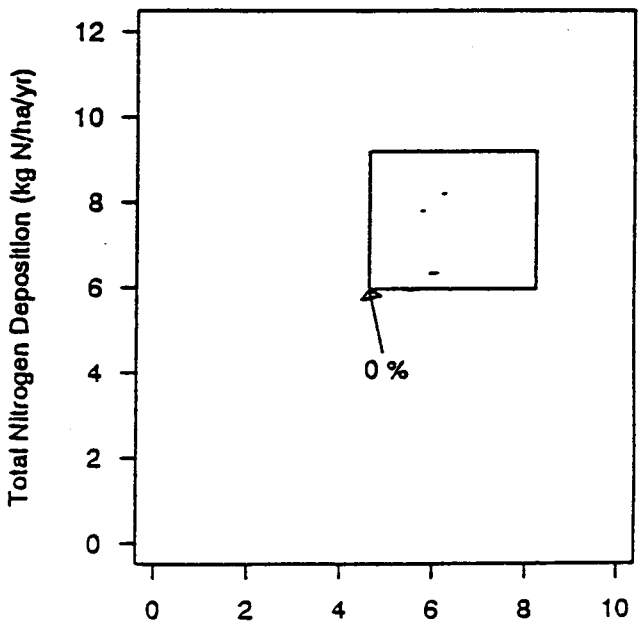


Percent of target population streams with pH<=6.0,
Southern Blue Ridge Region at Year 2015
where deposition=median regional @ year 2015.
pH estimated from empirical pH-ANC model.

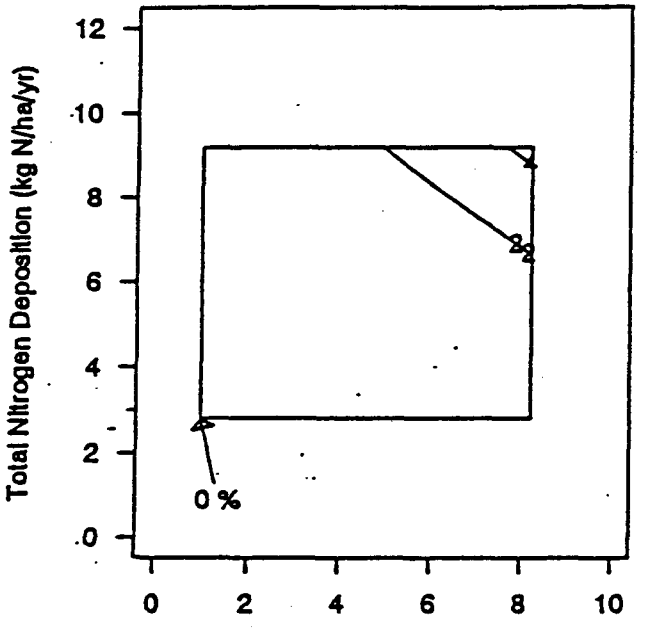


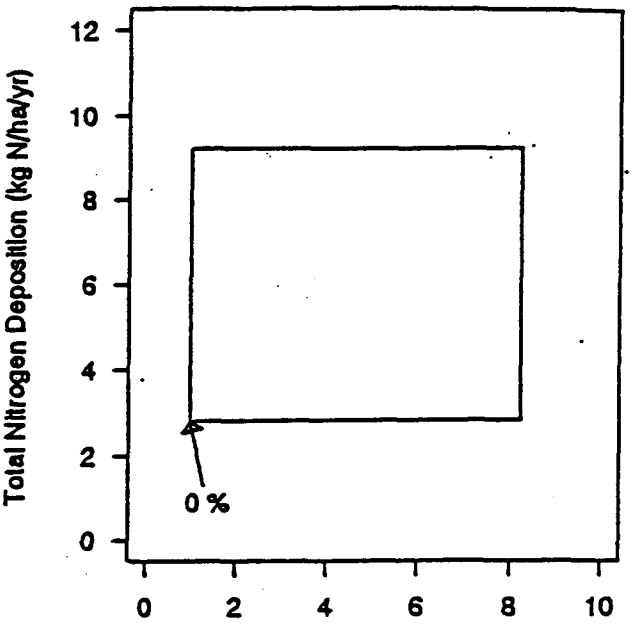


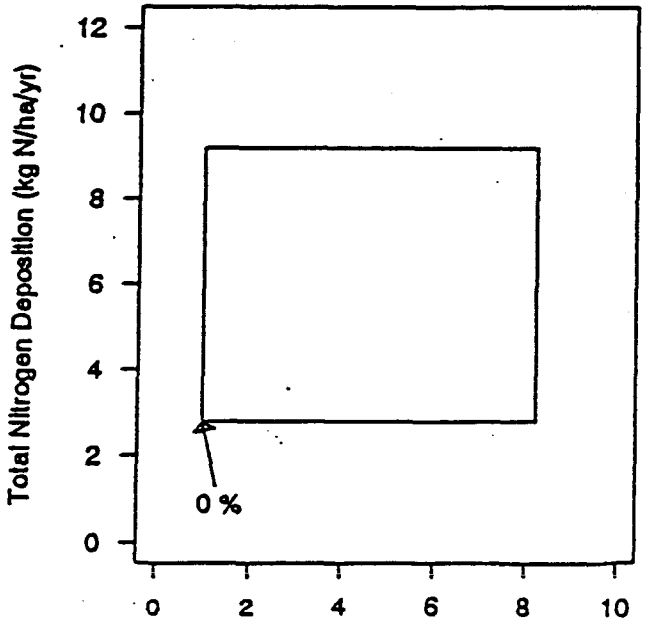


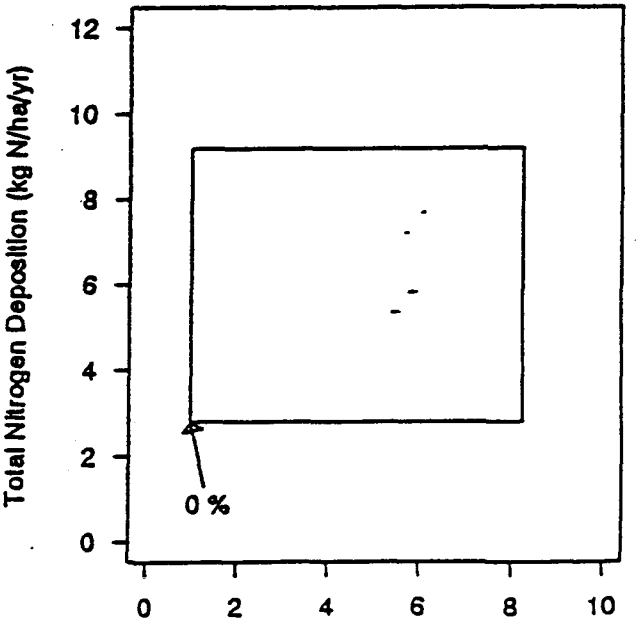


Percent of target population streams with ANC<=0,
Southern Blue Ridge Region at Year 2040
where deposition=median regional @ year 2020.

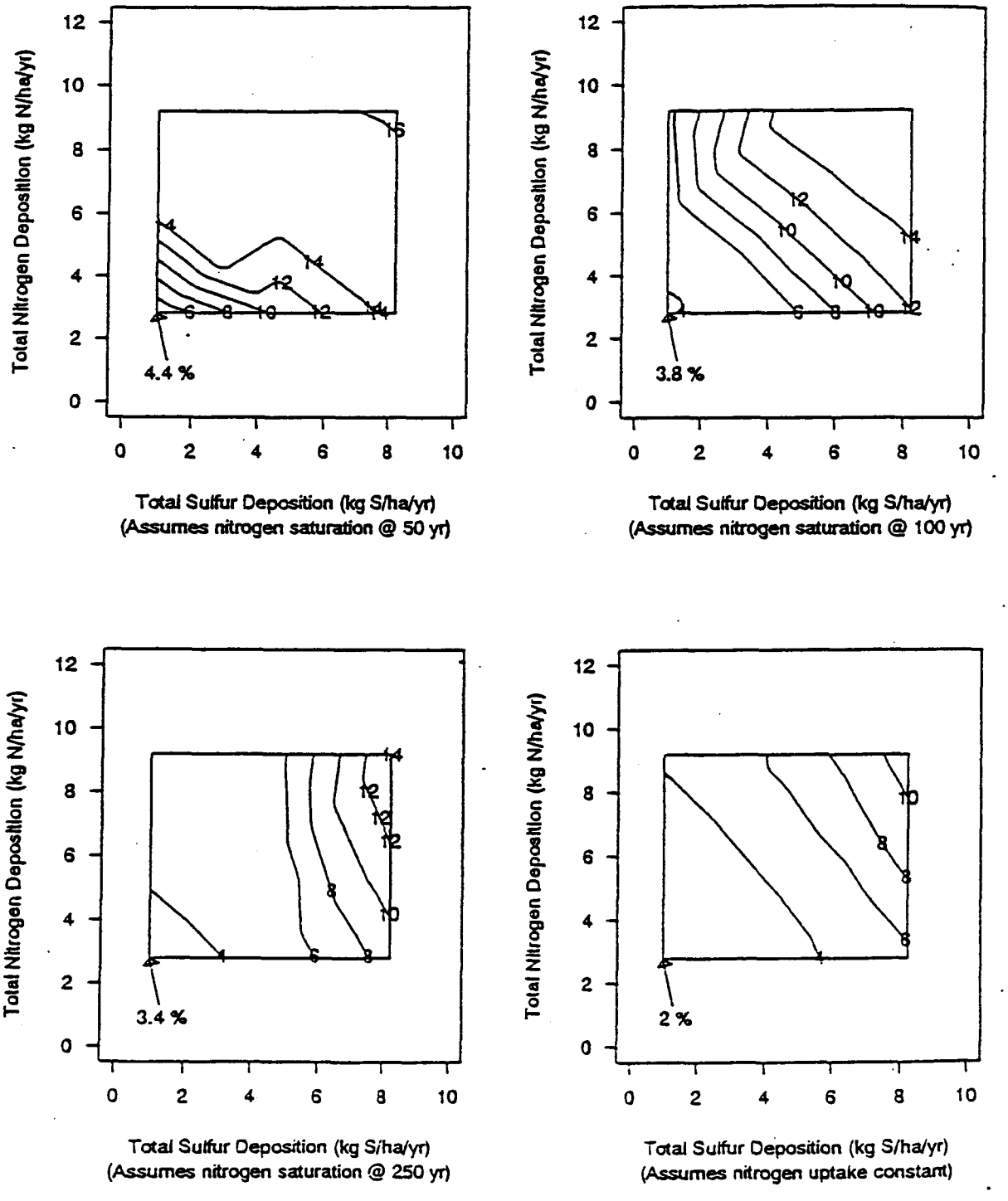




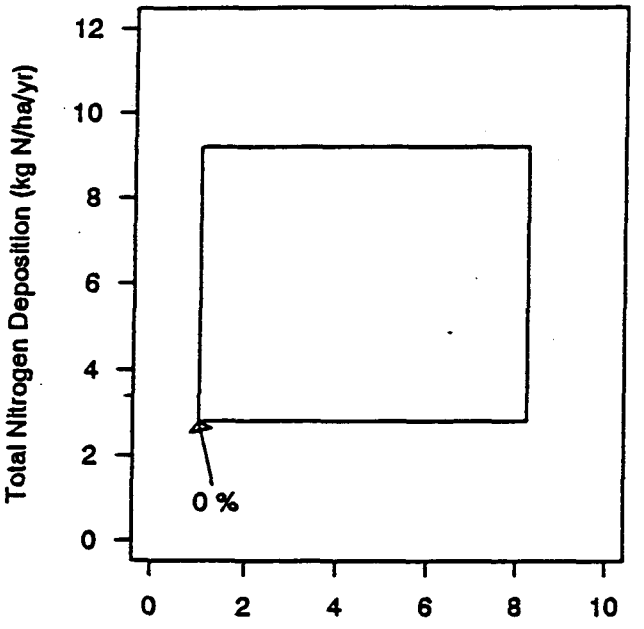


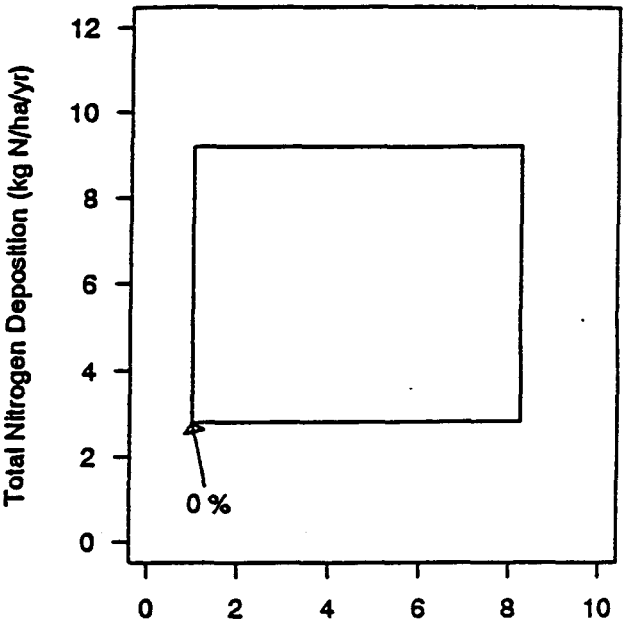


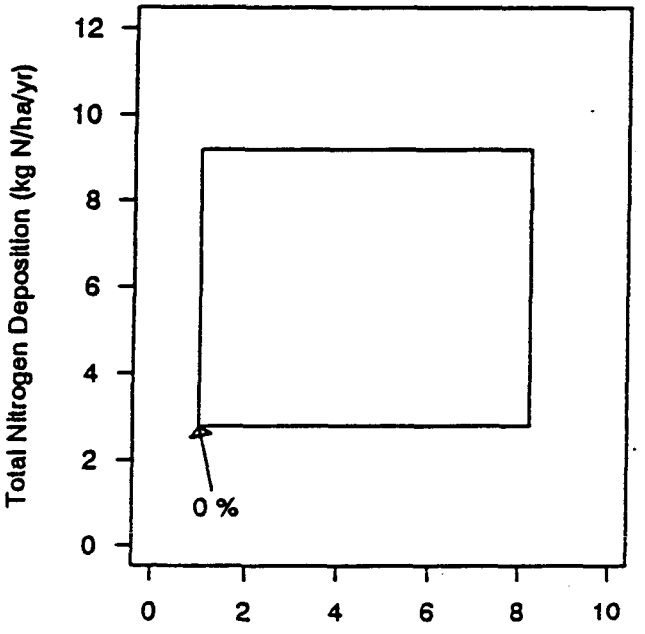
Percent of target population streams with ANC<=50,
Southern Blue Ridge Region at Year 2040
where deposition=median regional @ year 2020.

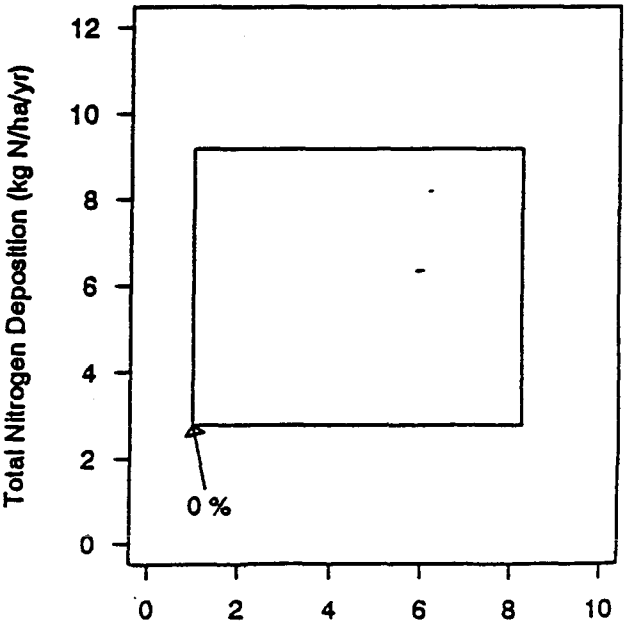


Percent of target population streams with pH<=5.0,
Southern Blue Ridge Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

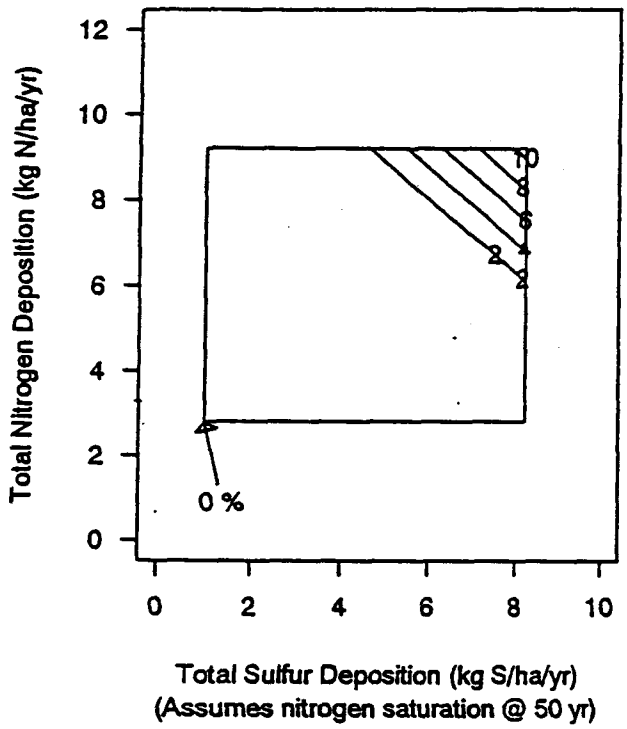


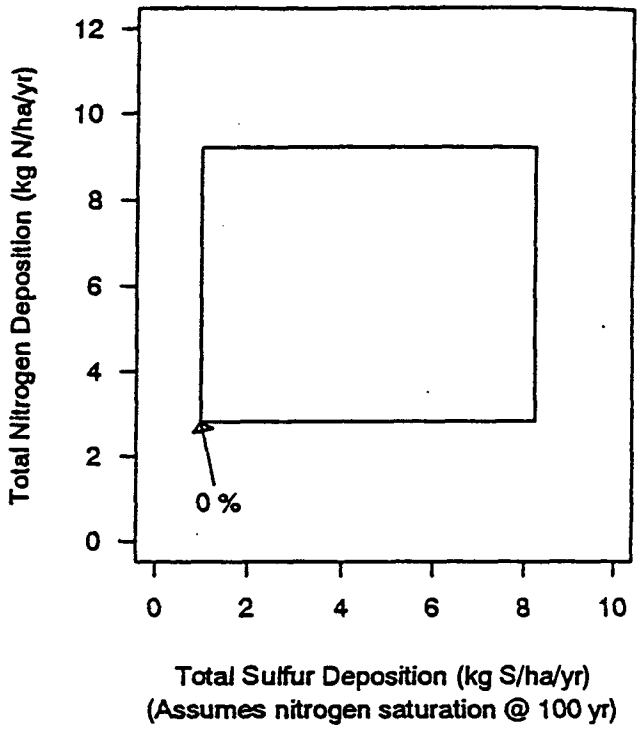


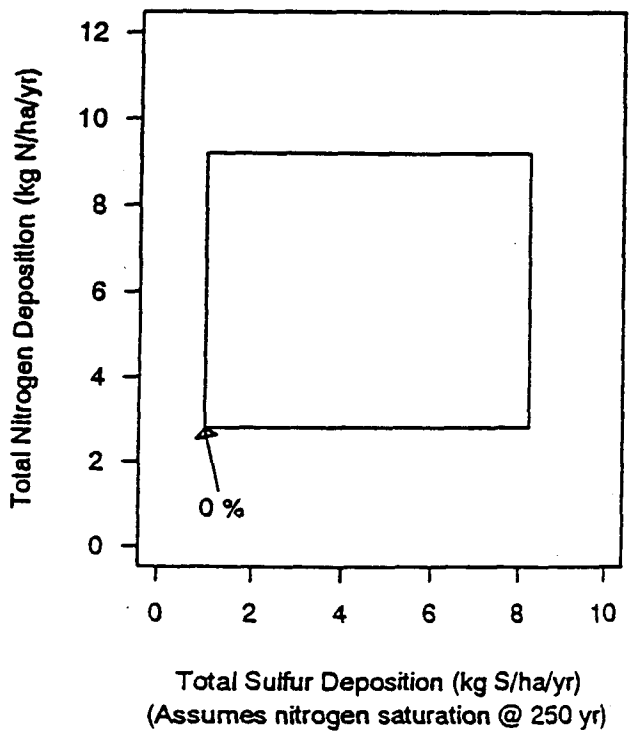


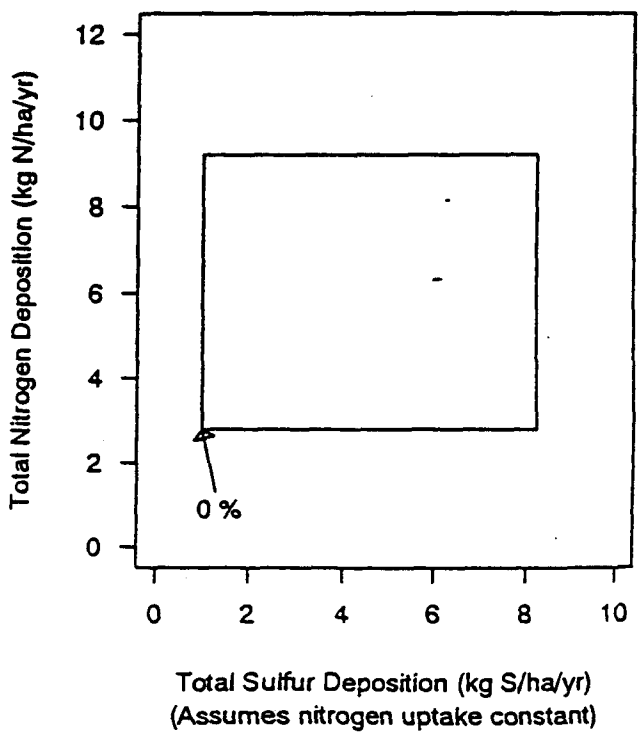


Percent of target population streams with pH<=5.5,
Southern Blue Ridge Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.

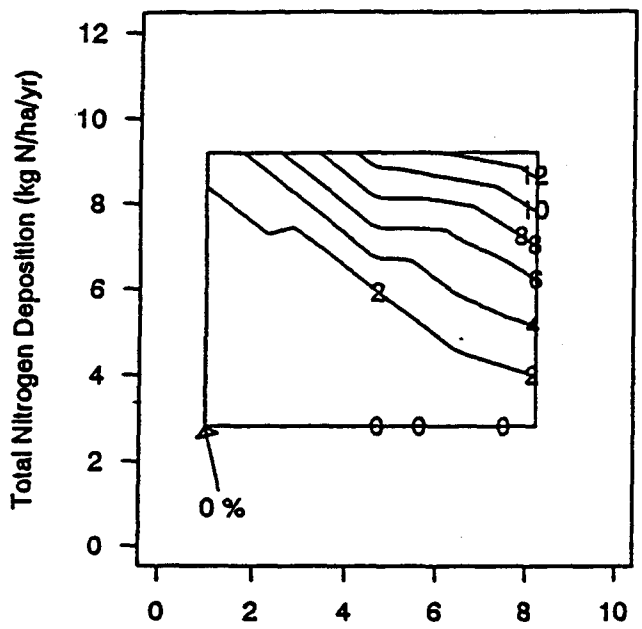


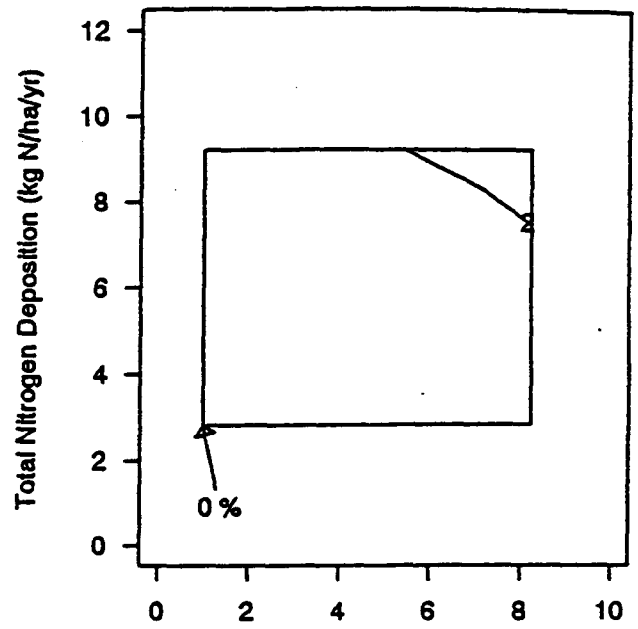


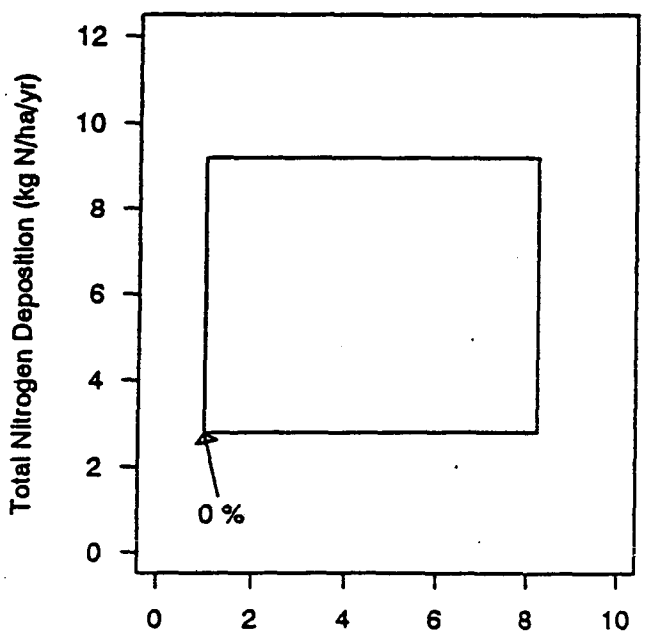


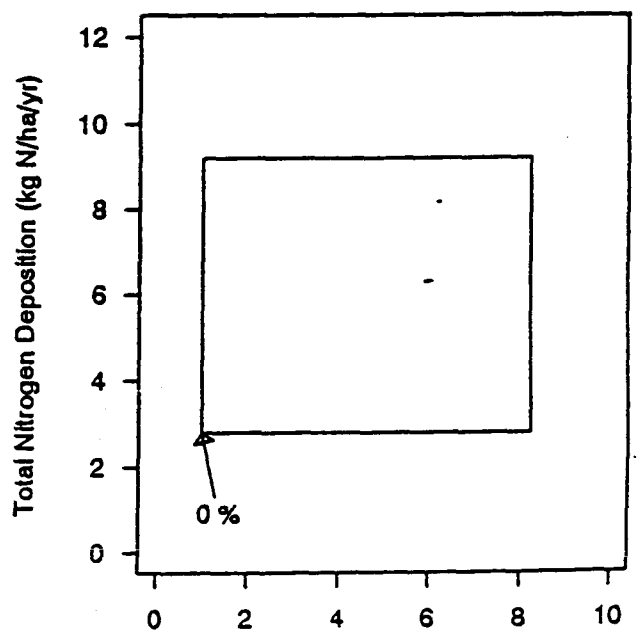


Percent of target population streams with pH<=6.0,
Southern Blue Ridge Region at Year 2040
where deposition=median regional @ year 2020.
pH estimated from empirical pH-ANC model.









APPENDIX C

RANGE OF INFLUENCE OF EMISSIONS FROM RADM TAGGED SUBREGIONS

APPENDIX C

RANGE OF INFLUENCE OF EMISSIONS FROM RADM TAGGED SUBREGIONS

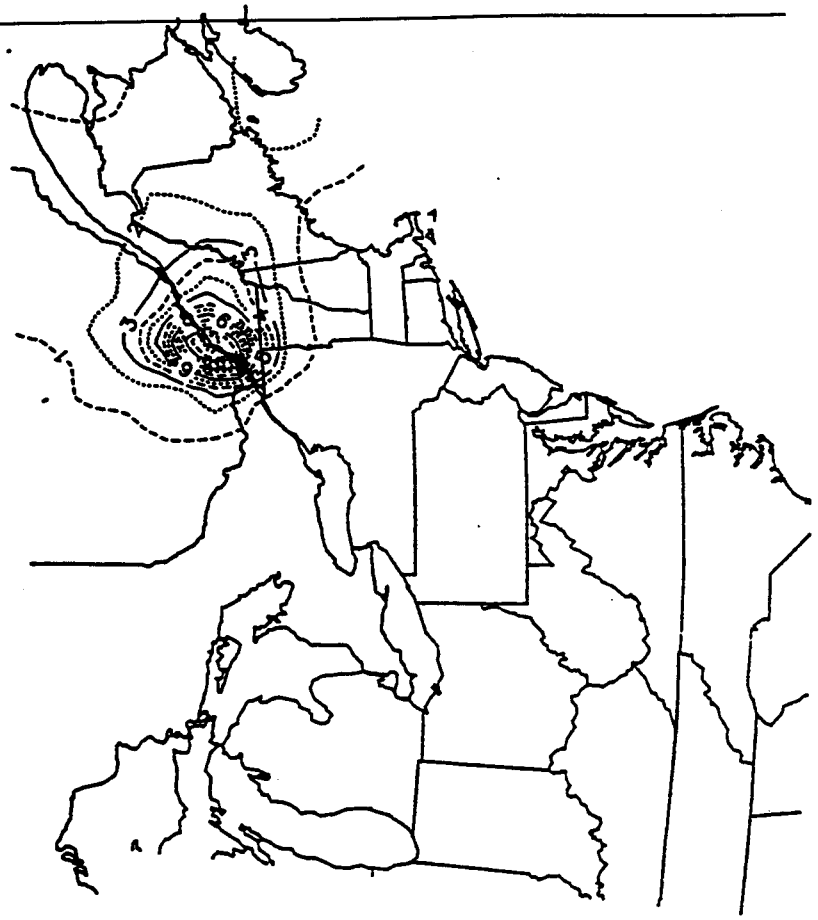
This report includes the first extensive use of a Eulerian model to study source-receptor relationships. Source-receptor relationships are used in this report to analyze changes in sources of deposition from implementation of Title IV of the Clean Air Act Amendments of 1990 and to investigate the effectiveness of several geographically targeted emissions reductions strategies to achieving target loads in sensitive receptor regions. The Tagged Species Engineering Model[1] was developed under NAPAP to study such relationships. The Tagged Species Model gives the Eulerian RADM modeling system the capability to identify, for assessment purposes, the concentration and deposition fields attributable to specified SO_2 emissions sources in the presence of the full concentration fields. The Tagged Model preserves the oxidant competition across space and time. A tagging concept is applied in which additional, identical mass conservation equations are solved for a portion of the sulfur concentration field that originates from specific geographical locations within the full modeling domain. This allows tagged concentration fields and tagged wet and dry deposition to be identified and tracked in the model separate from, yet as portions of, the total sulfur chemical environment that is nonlinear and that produces the complete concentration and deposition fields.

Calculations from the Tagged Species Model illustrate the distances over which an SO_2 emissions source can have an influence. The results from this model permit the visualization of source attribution. Emissions from a subregion (see Exhibit 19 for the 53 tagged RADM subregions) have a range of influence is more than 1,000 kilometers. Typically, the range of influence of a subregion extends out to between 500 and 1,200 kilometers. The difference in scale of influence is primarily due to meteorology. A number of meteorological factors influence the existence of dominant transport directions and determine how sources of SO_2 emissions influence nearby regions. Key factors are the position of the jet stream, which moves storms across the upper Mid-West; the influence of the Appalachian Mountains on winds and rainfall patterns; the Bermuda highs (stagnation) that move Ohio River Valley emissions in a counter-clockwise direction; and the ocean and Gulf Coast weather that produces lighter winds and more convective conditions, including a typically large proportion of convective clouds across the southern states. Thus, the patterns and ranges of source influence can vary. Models, such as those in the RADM system, help to interpret and explain the deposition at receptors of interest.

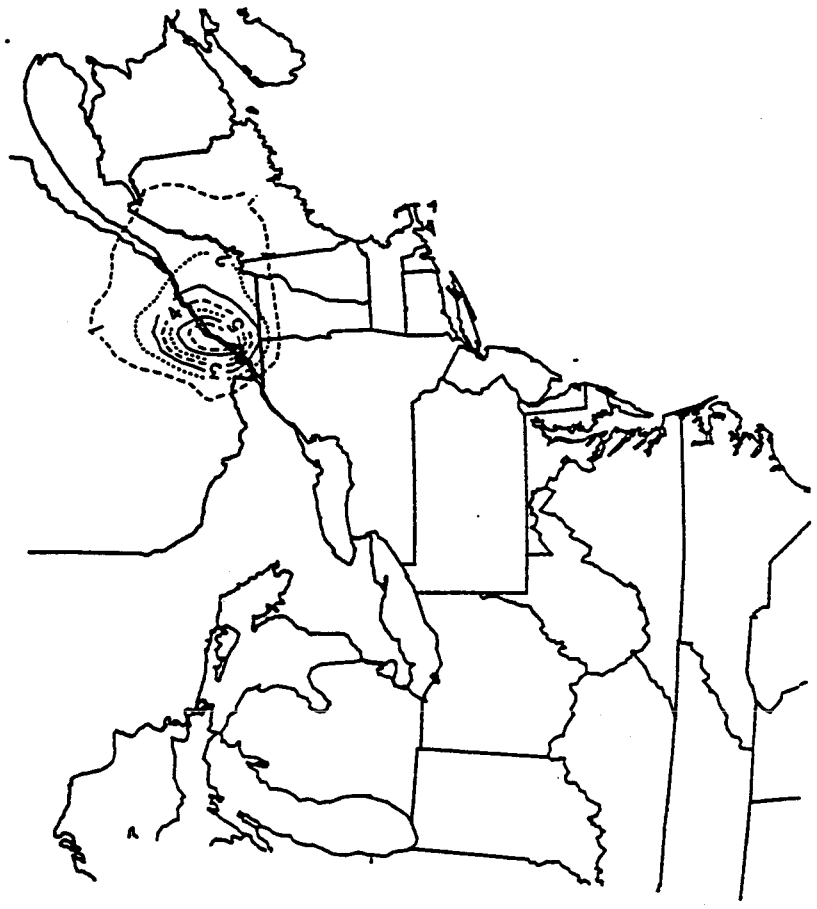
This appendix contains maps of which show the proportion of total annual sulfur deposition contributed by each of the 53 tagged RADM subregions in 1985 and projected for 2010 with implementation of Title IV.

[1] McHenry, J.N., F.S. Binkowski, R.L. Dennis, J.S. Chang, and D. Hopkins. 1992. The tagged species engineering model (TSEM). *Atmospheric Environment* 26A(8):1427–1443.

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 01, MONTREAL AREA



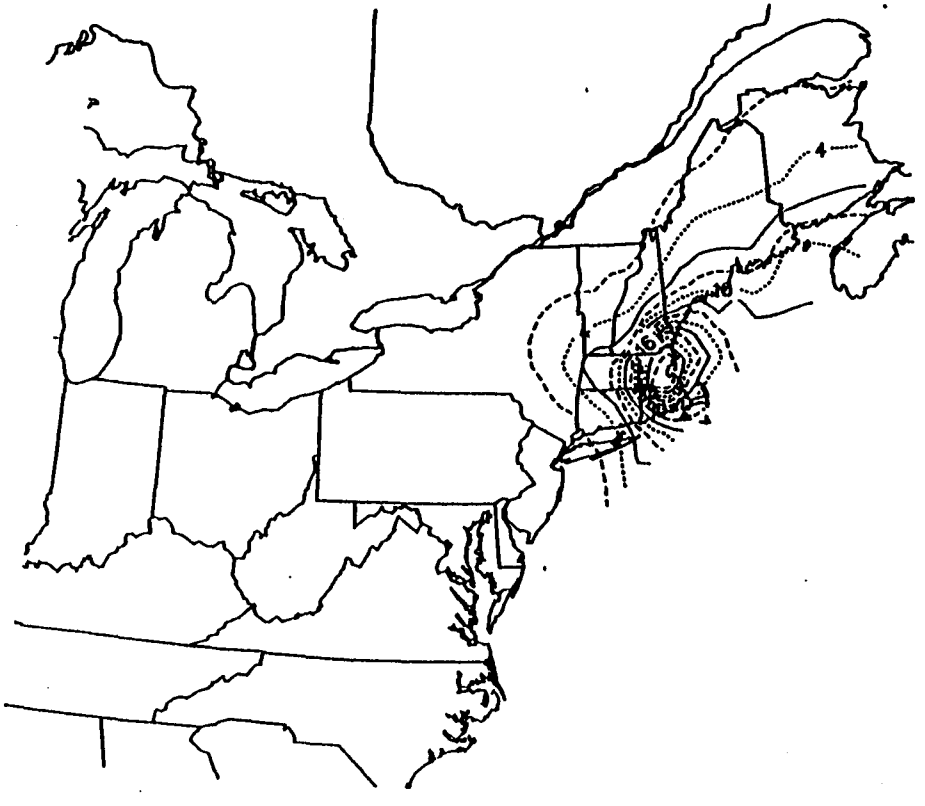
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 01, MONTREAL AREA



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION

1985 EMISSIONS

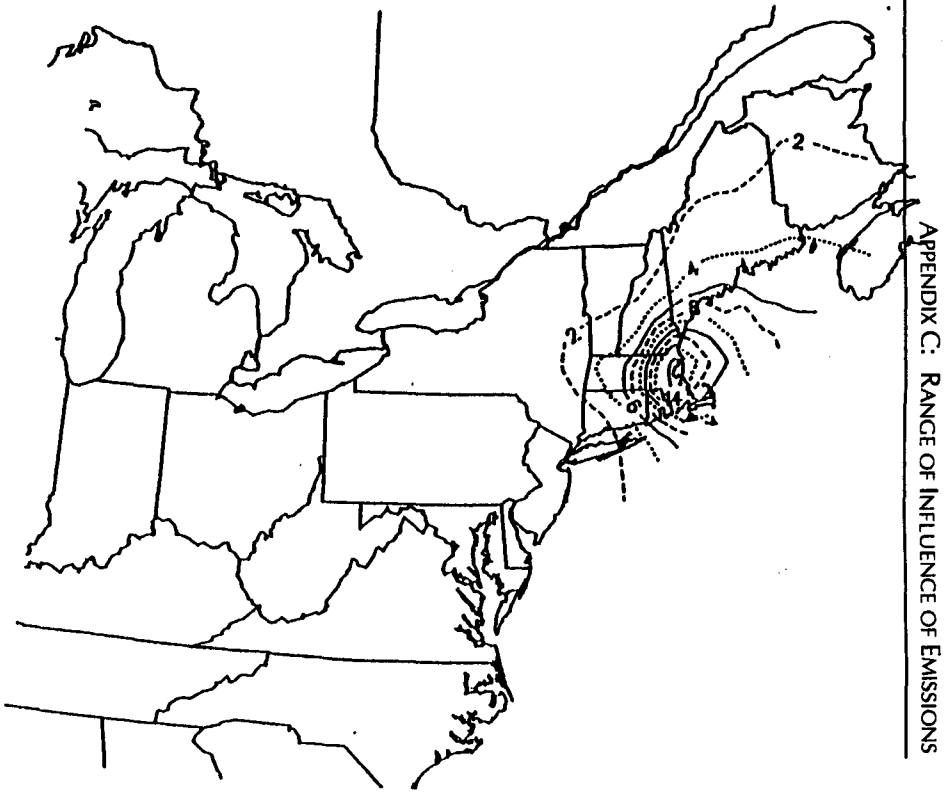
SUBREGION 02, NH/MA BORDER



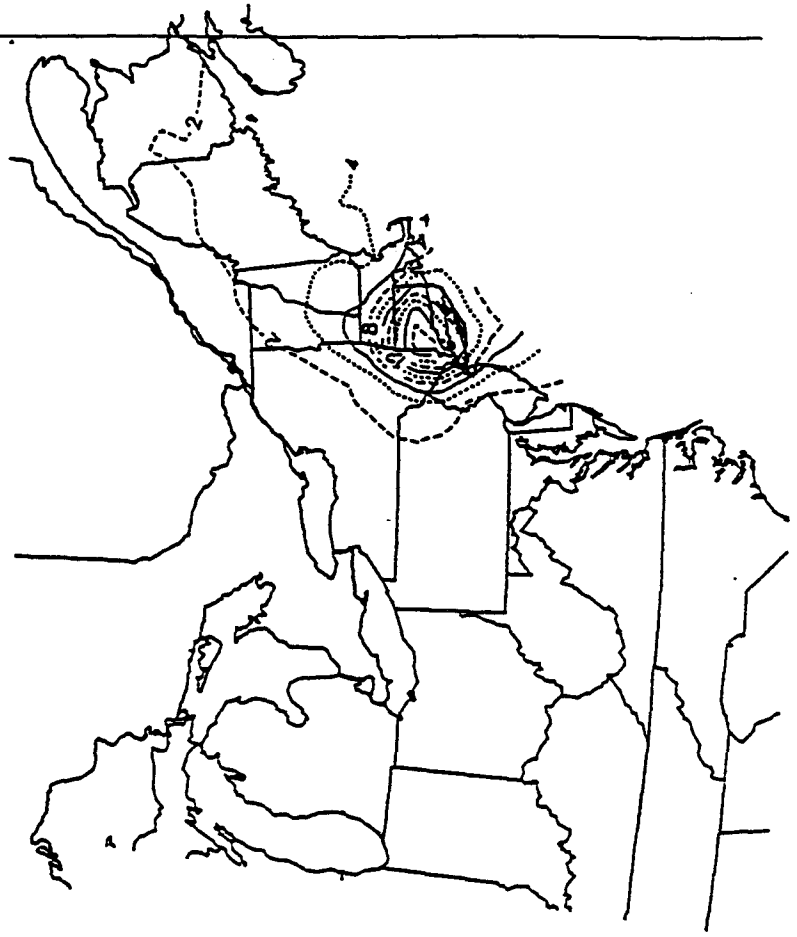
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION

2010 EMISSIONS

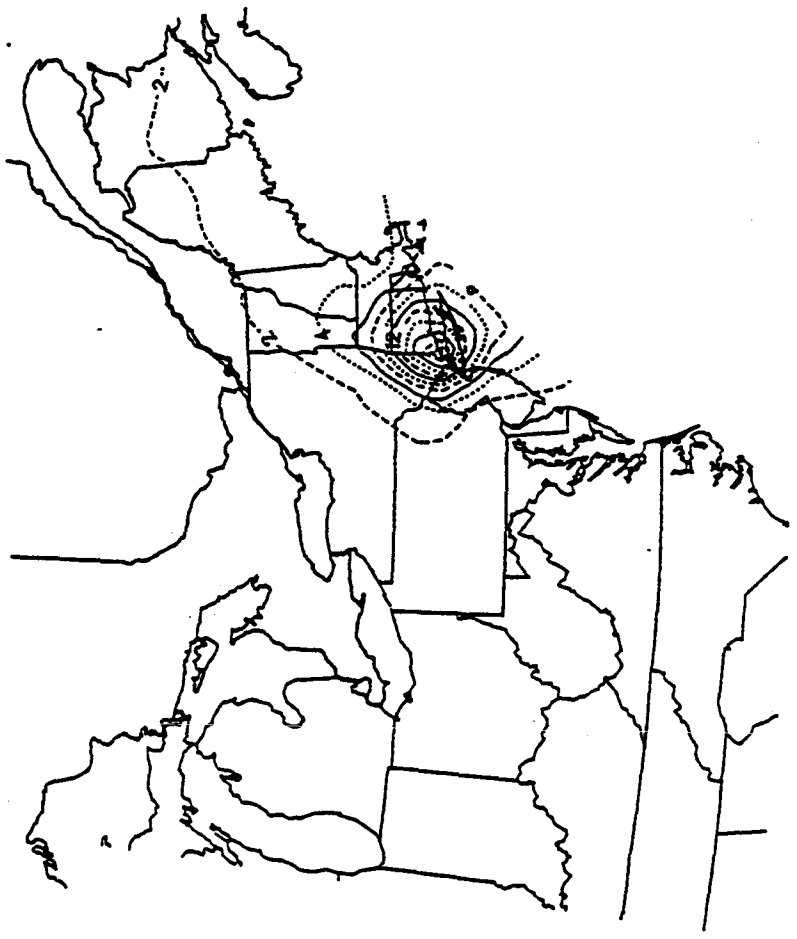
SUBREGION 02, NH/MA BORDER



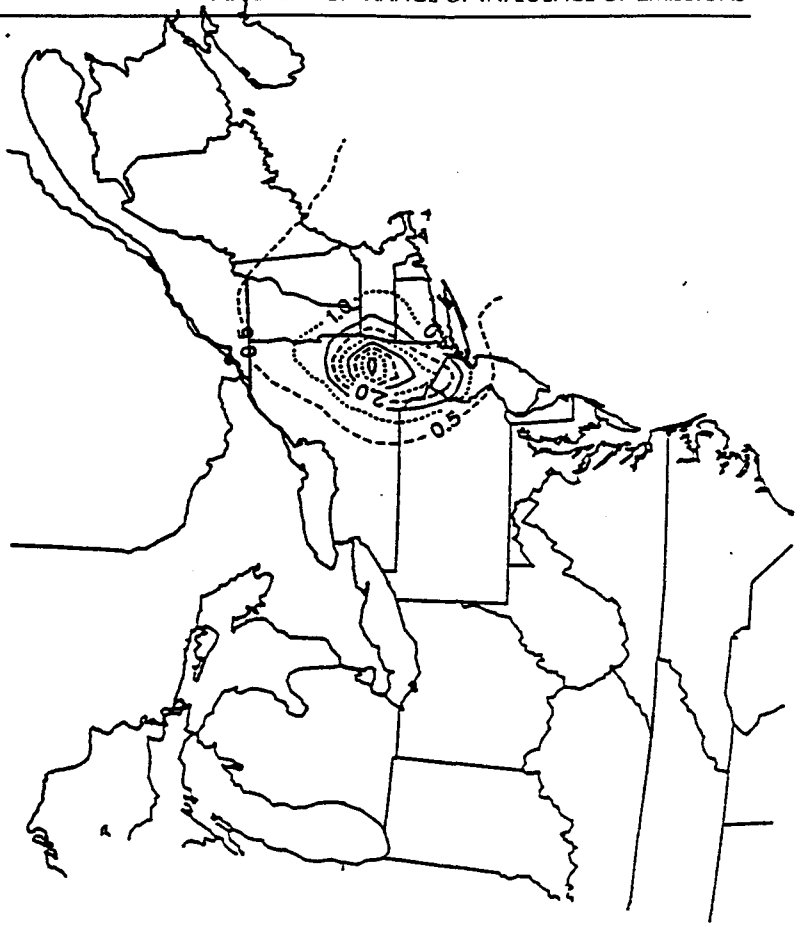
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 03, NYC/CT



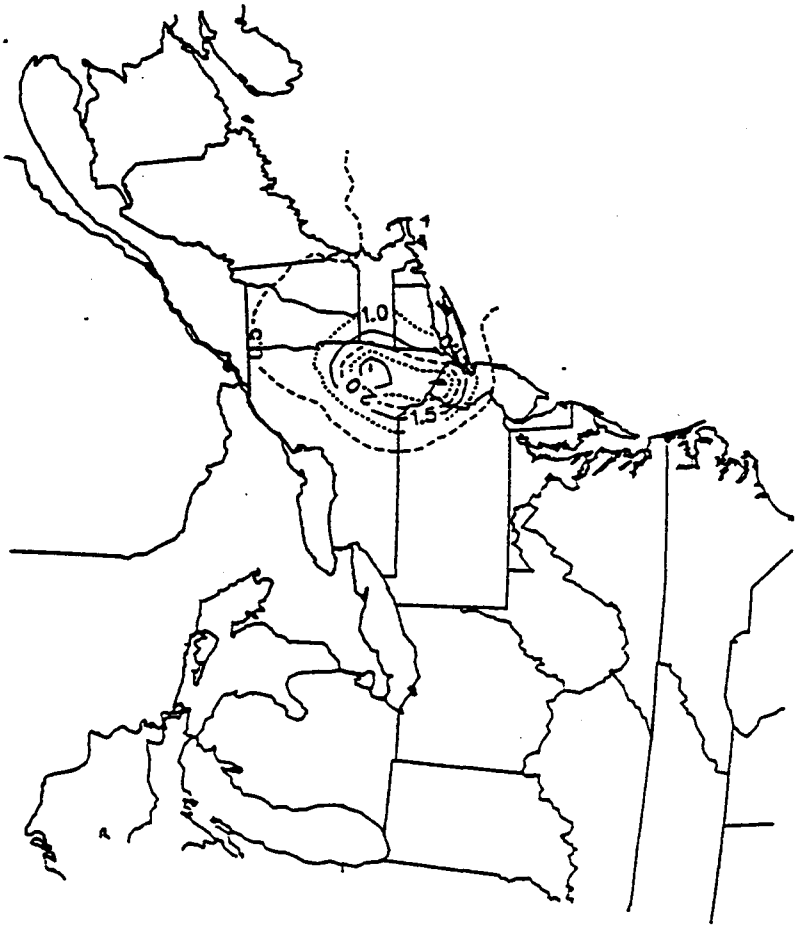
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 03, NYC/CT



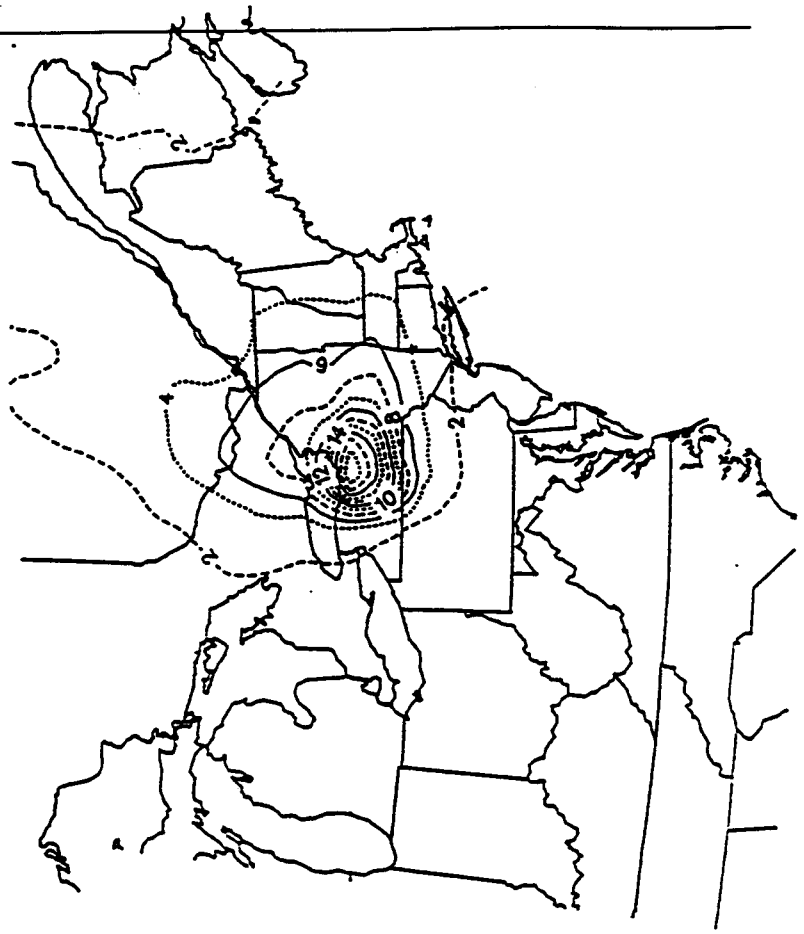
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 04, SOUTHEAST NY



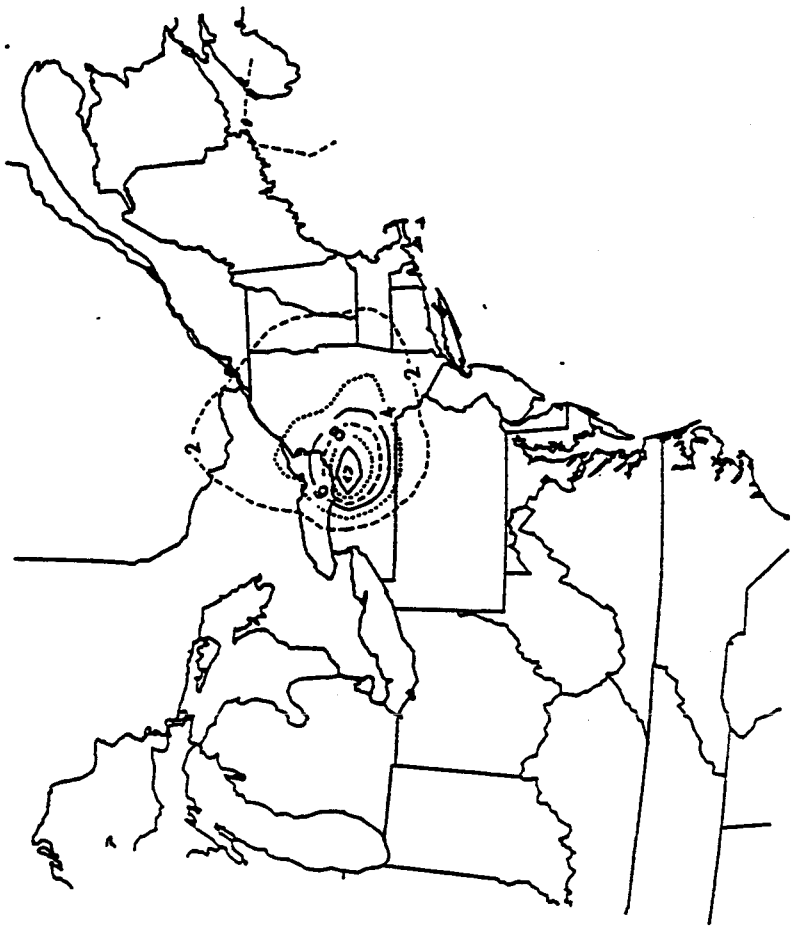
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 04, SOUTHEAST NY



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 05, SOUTHERN TIER NY



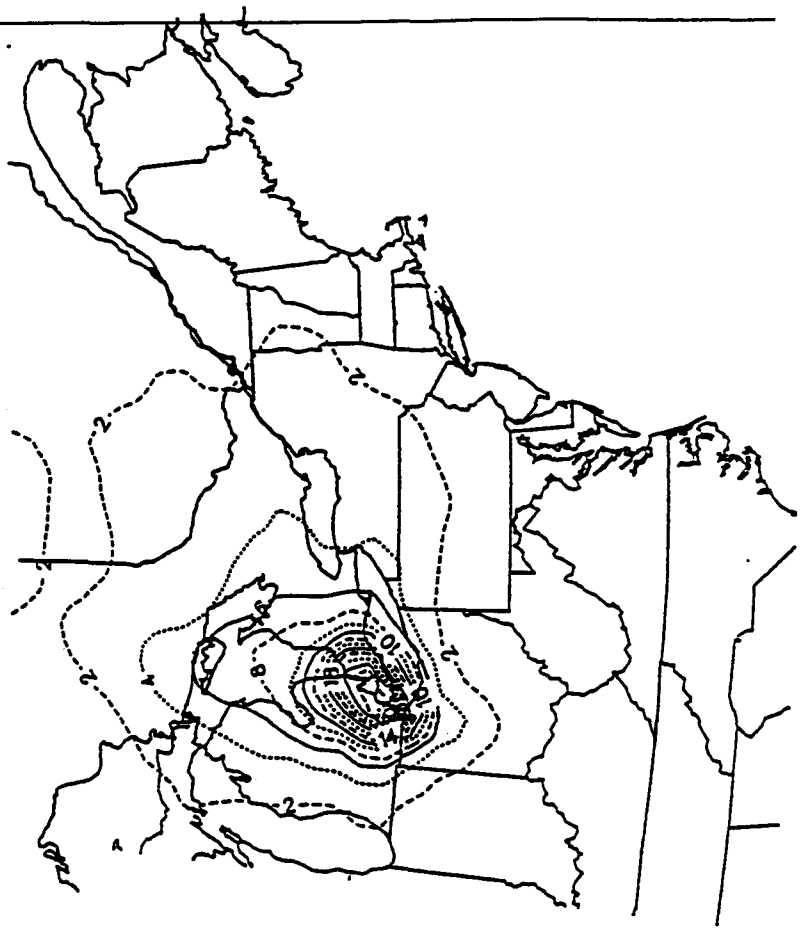
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 05, SOUTHERN TIER NY



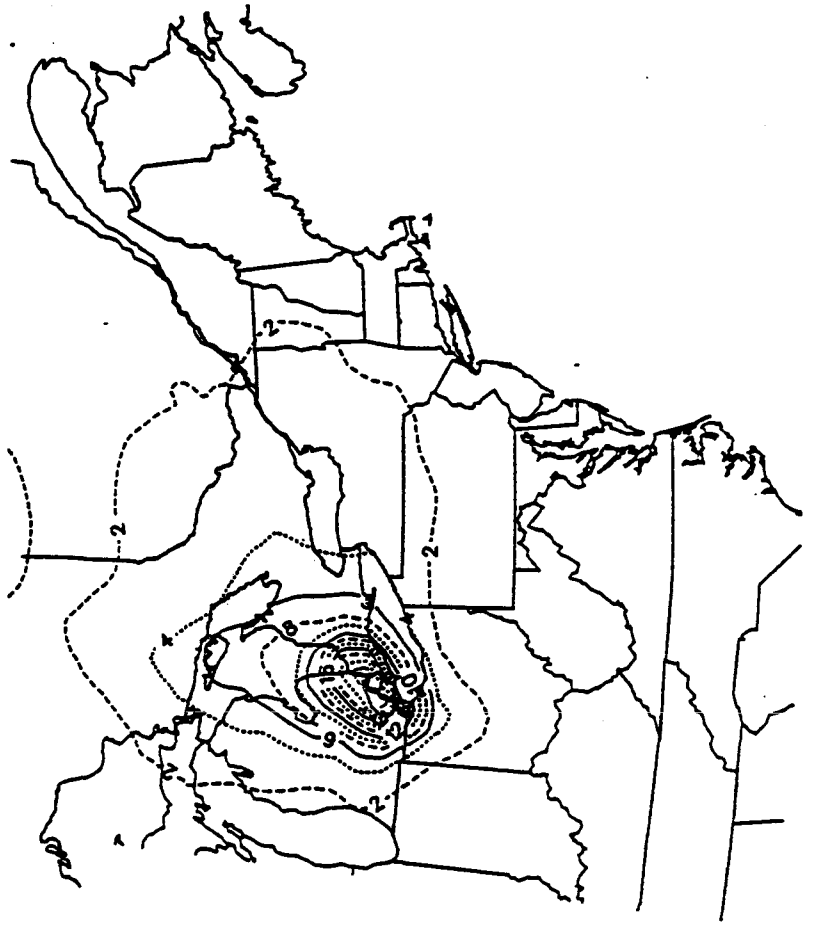
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 06, TORONTO AREA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 06, TORONTO AREA

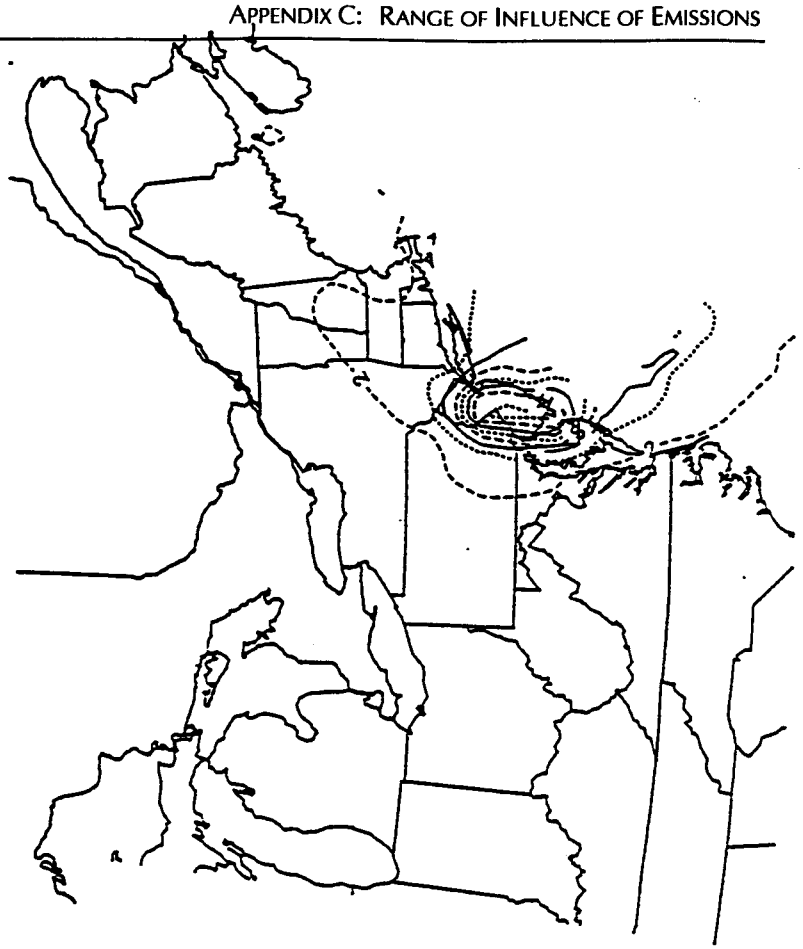
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 07, DETROIT AREA



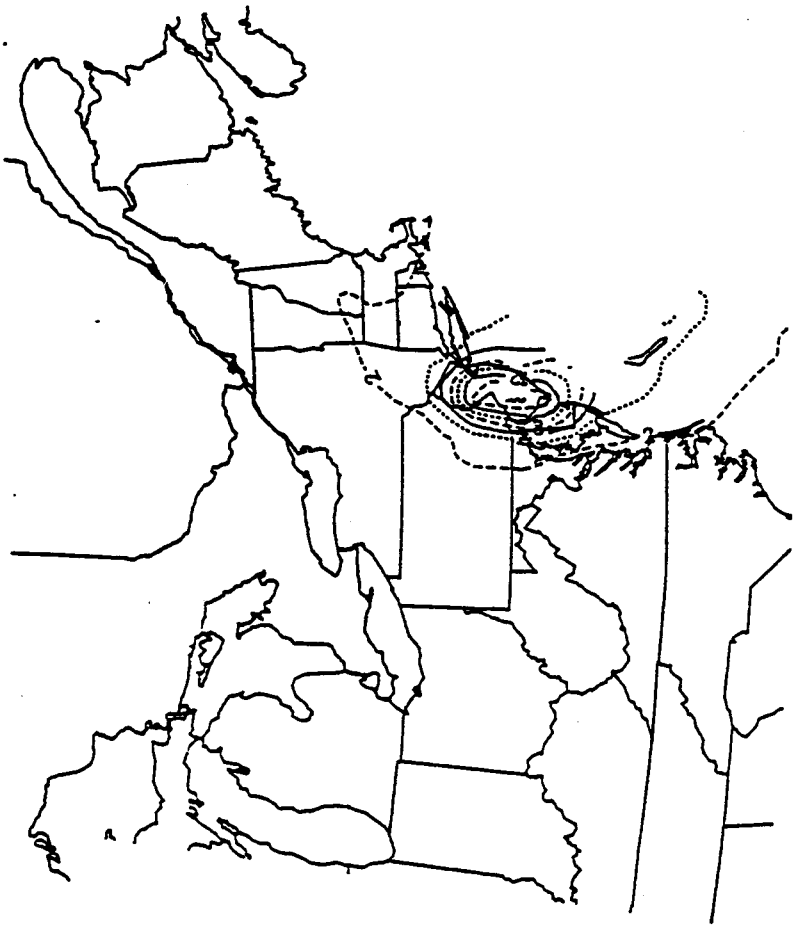
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 07, DETROIT AREA



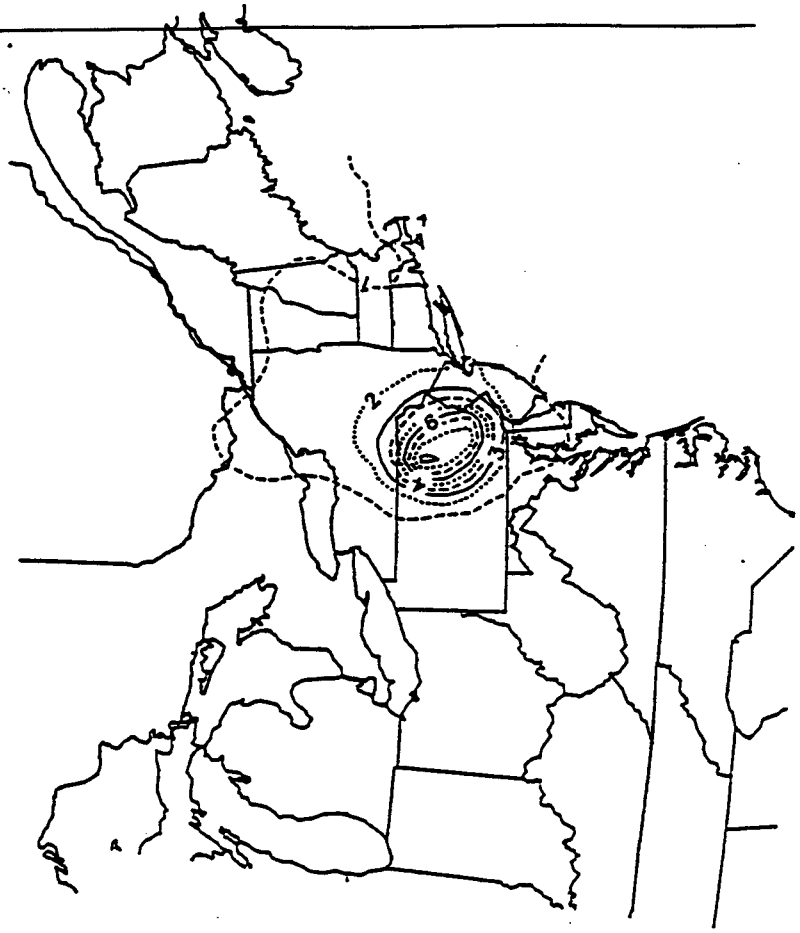
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 08, CENTRAL/SOUTHERN NJ



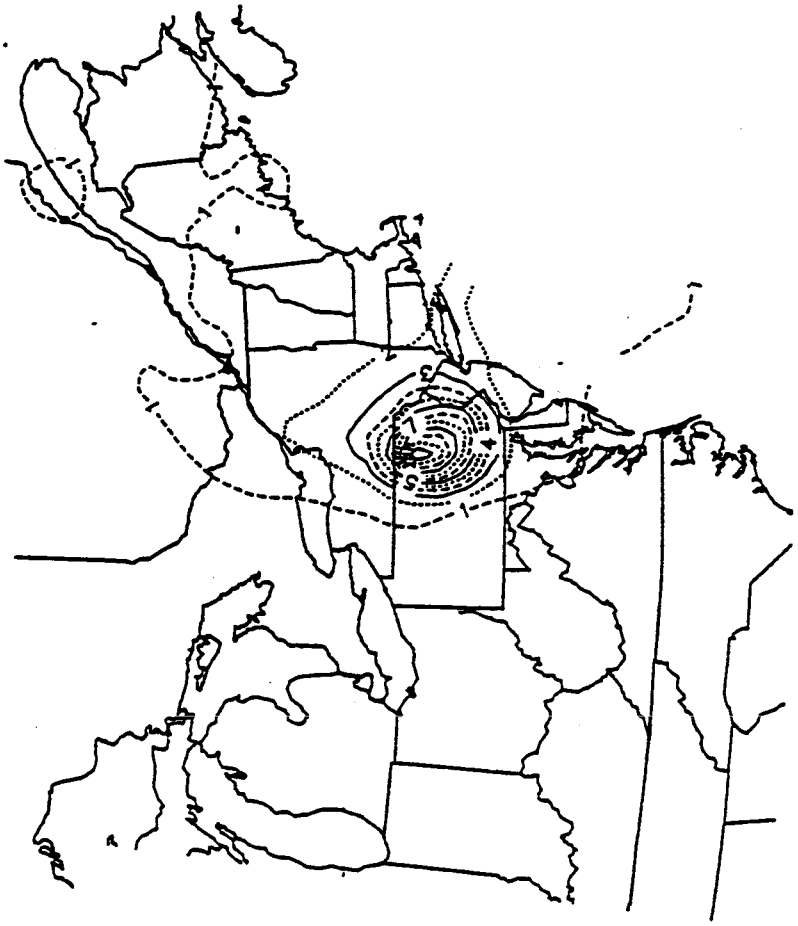
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 08, CENTRAL/SOUTHERN NJ



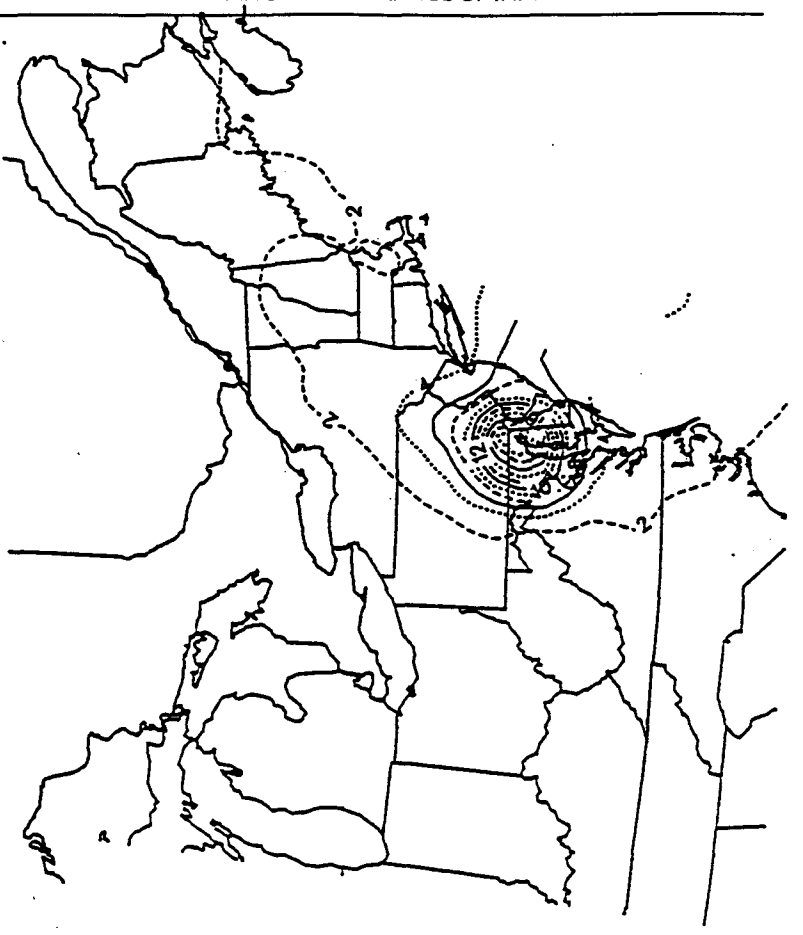
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 09, EASTERN PA



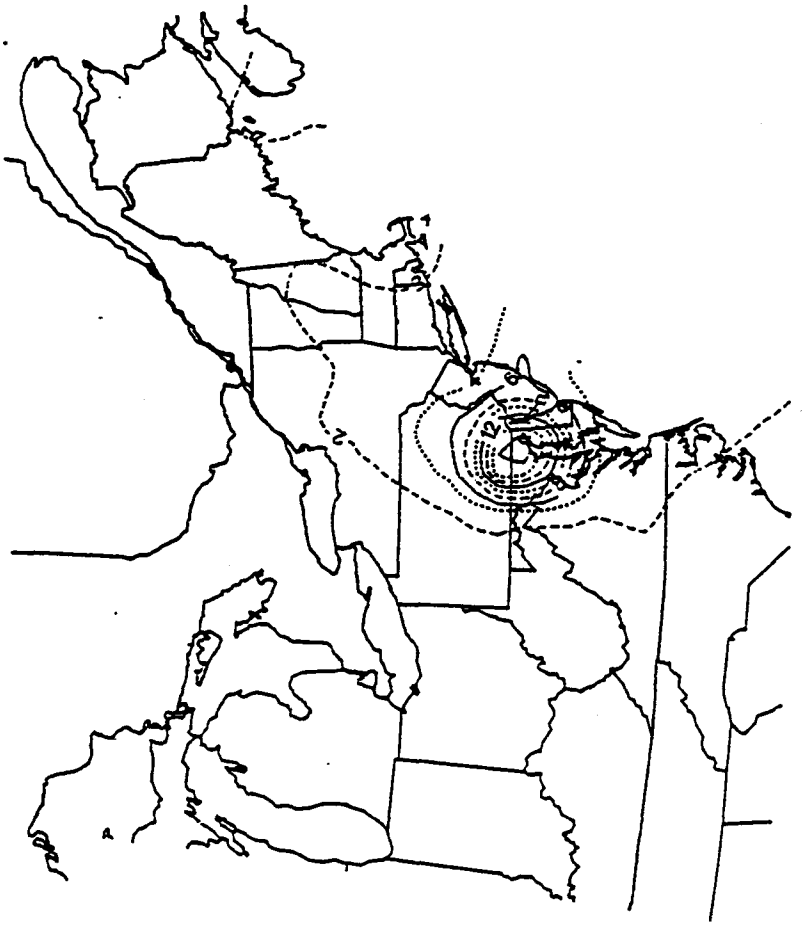
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 09, EASTERN PA



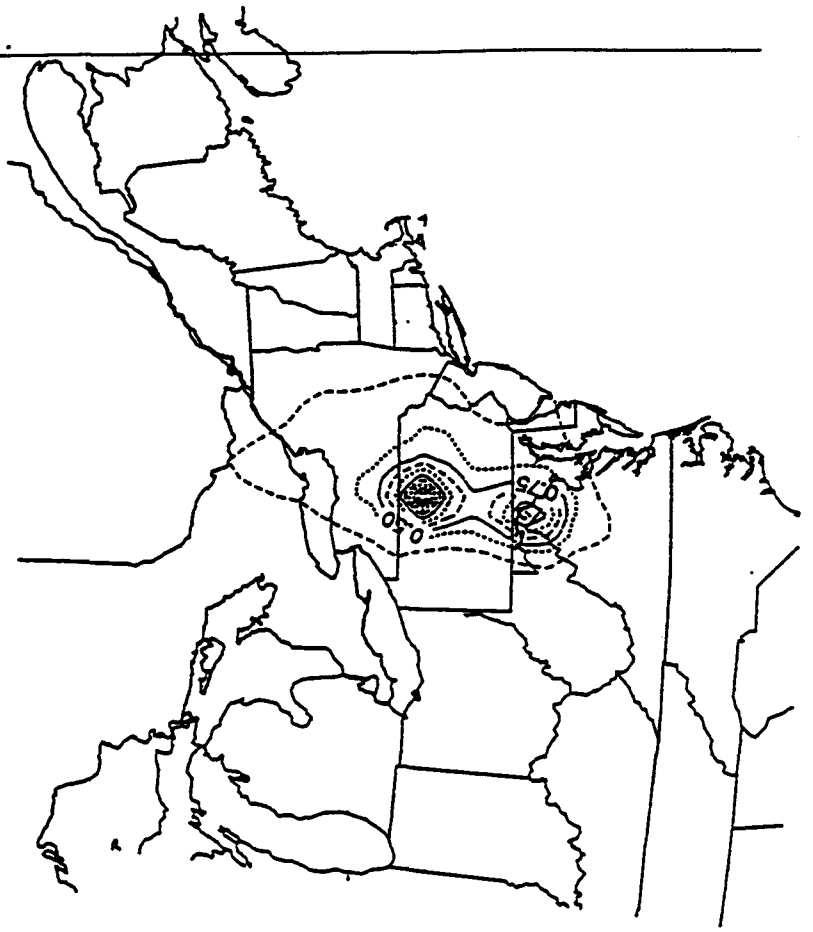
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 10, SOUTHERN PA/MID



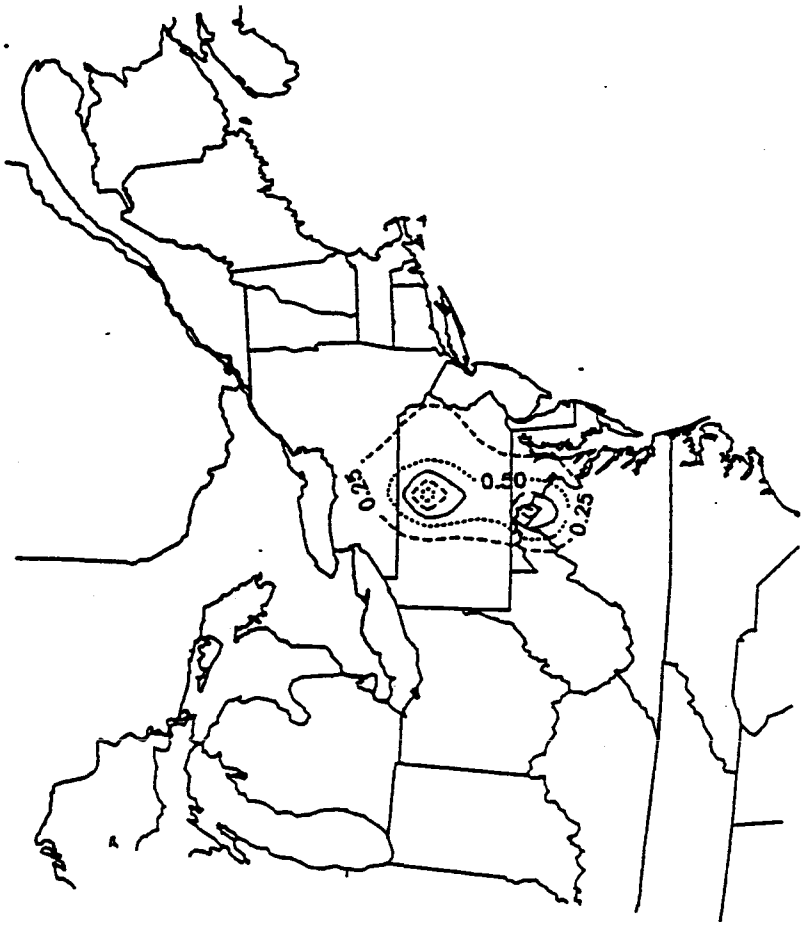
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 10, SOUTHERN PA/MID



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 11, CENTRAL PA



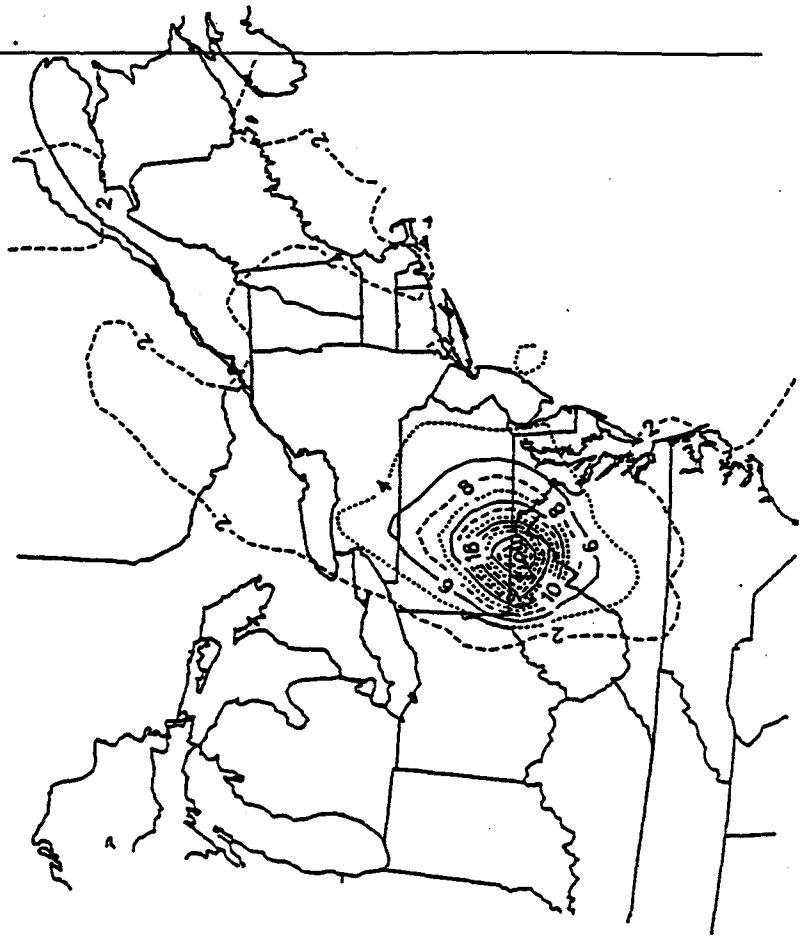
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 11, CENTRAL PA



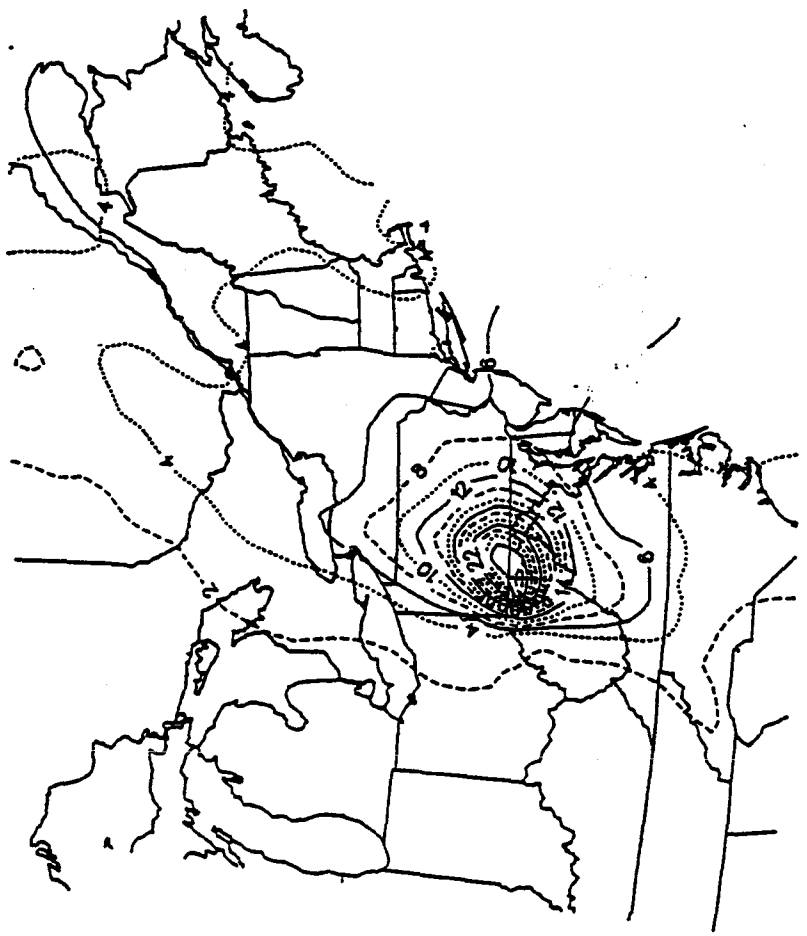
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 12, NORTHWEST PA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 12, NORTHWEST PA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 13, SOUTHWEST PA/NORTHERN WV



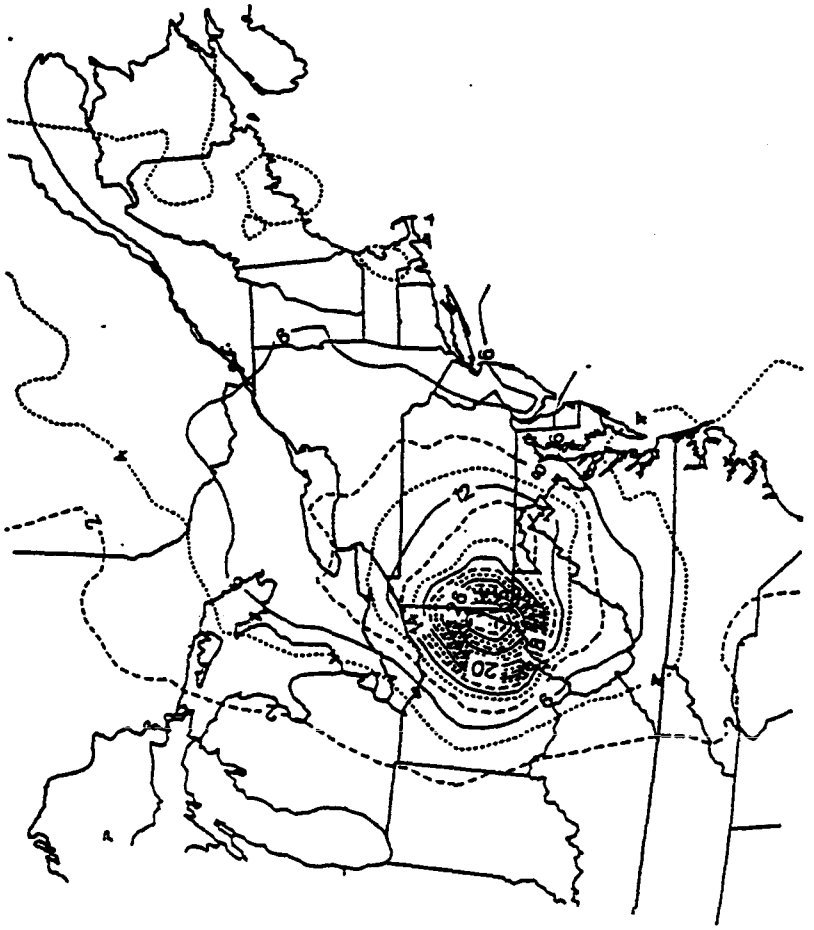
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 13, SOUTHWEST PA/NORTHERN WV



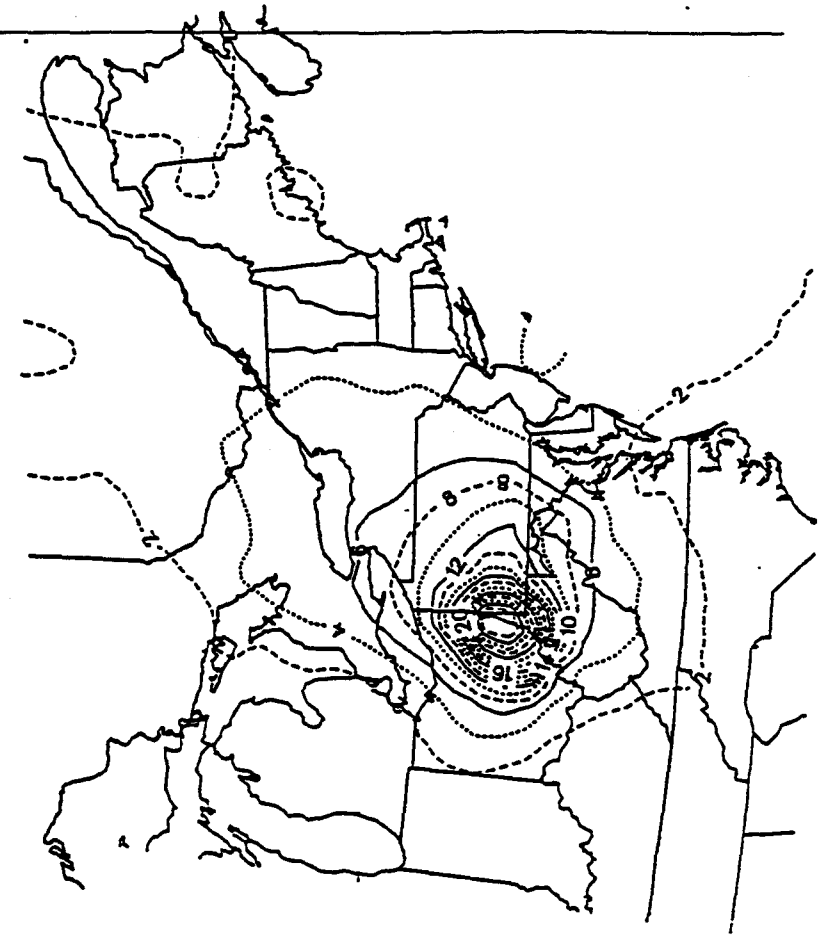
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 14, CLEVELAND AREA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 14, CLEVELAND AREA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 15, OH/WV/PA BORDER



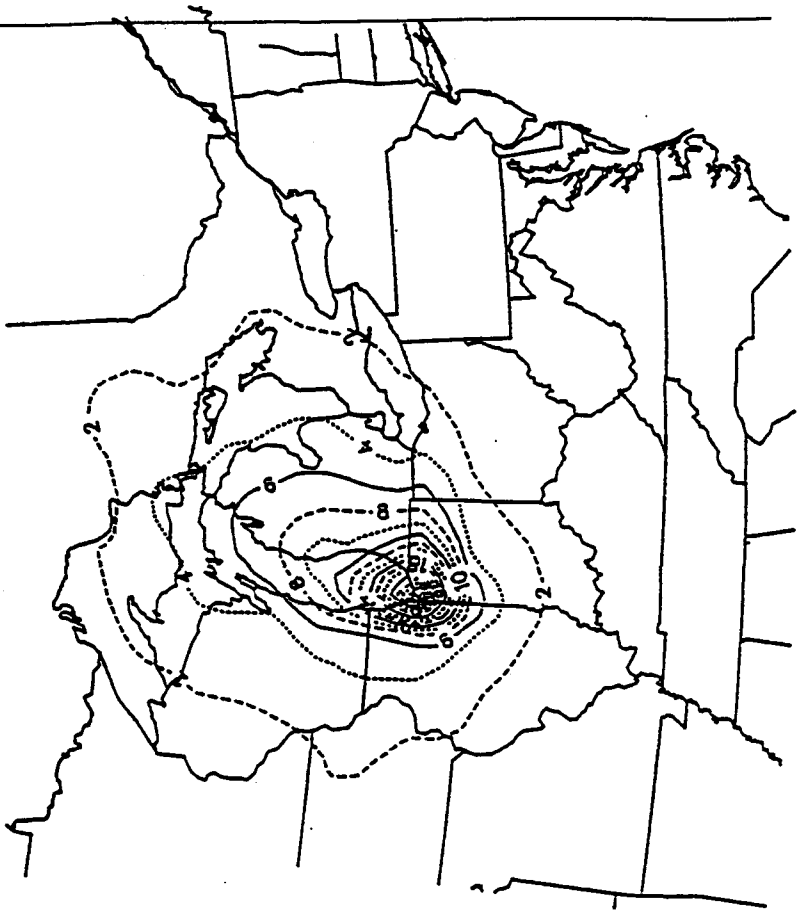
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 15, OH/WV/PA BORDER



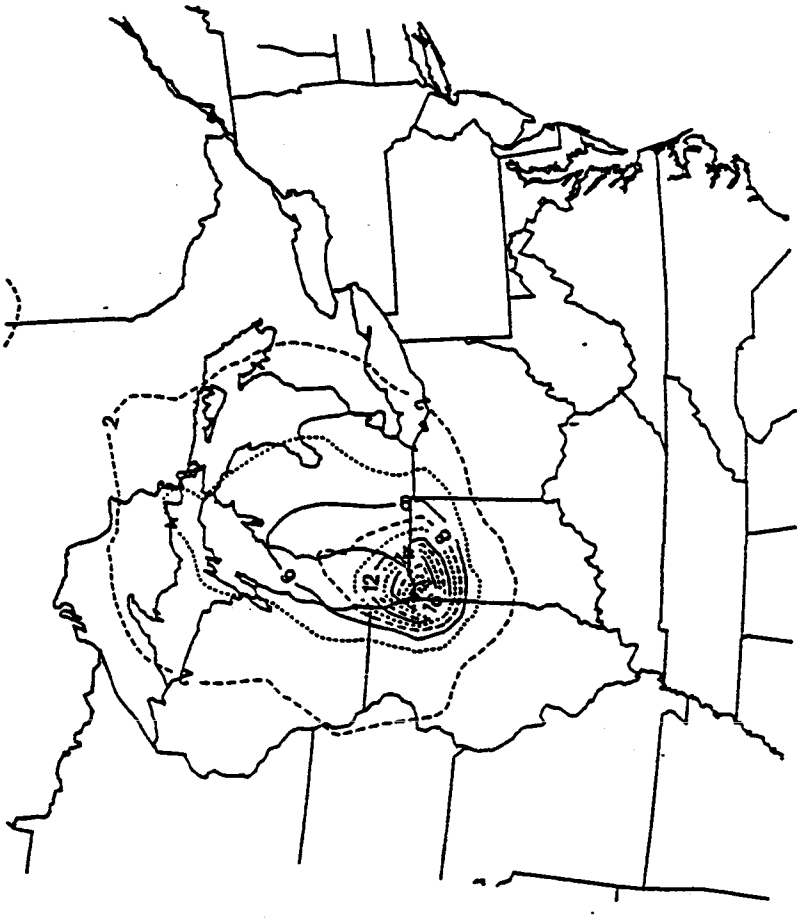
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 16, NORTHWEST OH/EASTERN IN

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 16, NORTHWEST OH/EASTERN IN

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 17, CHICAGO AREA



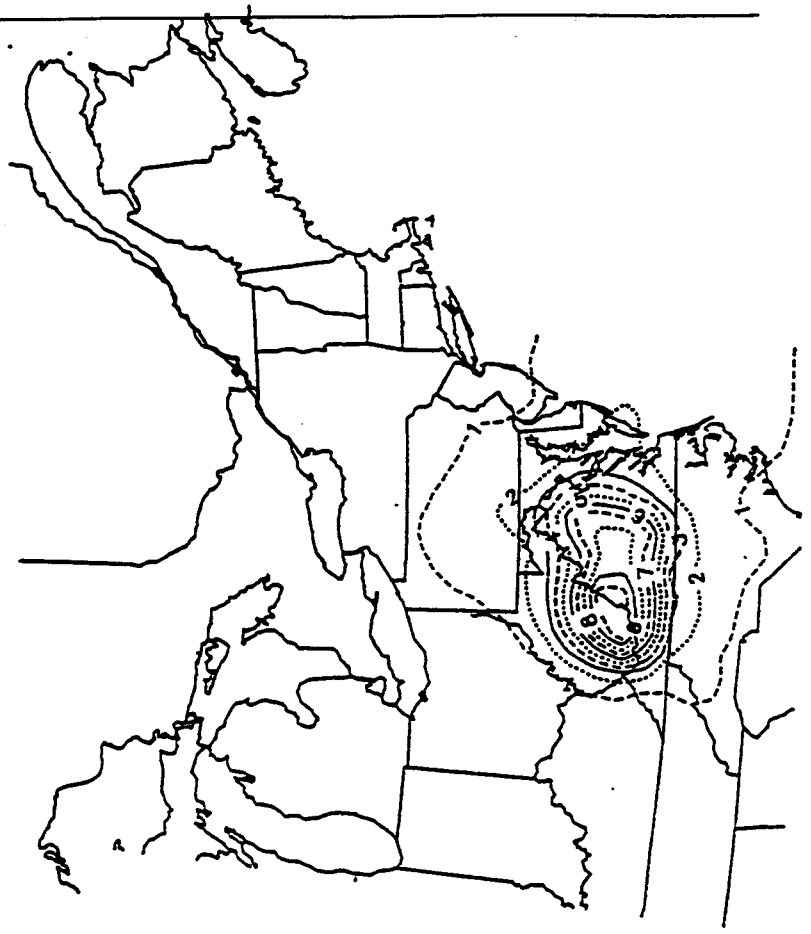
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 17, CHICAGO AREA



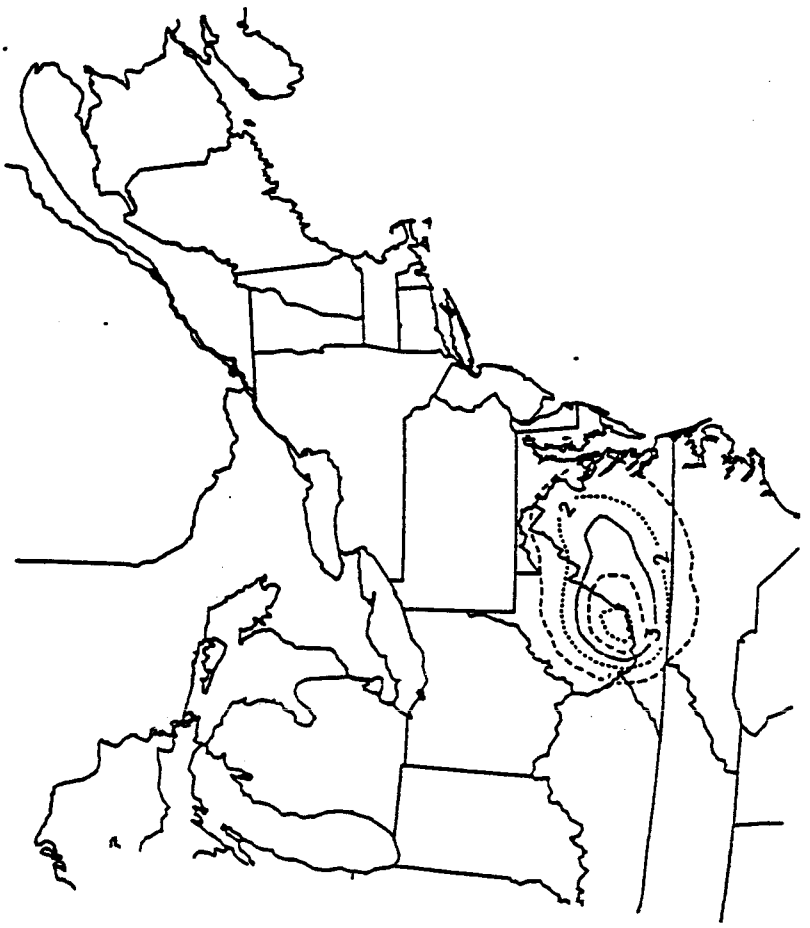
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 18, EASTERN VA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 18, EASTERN VA

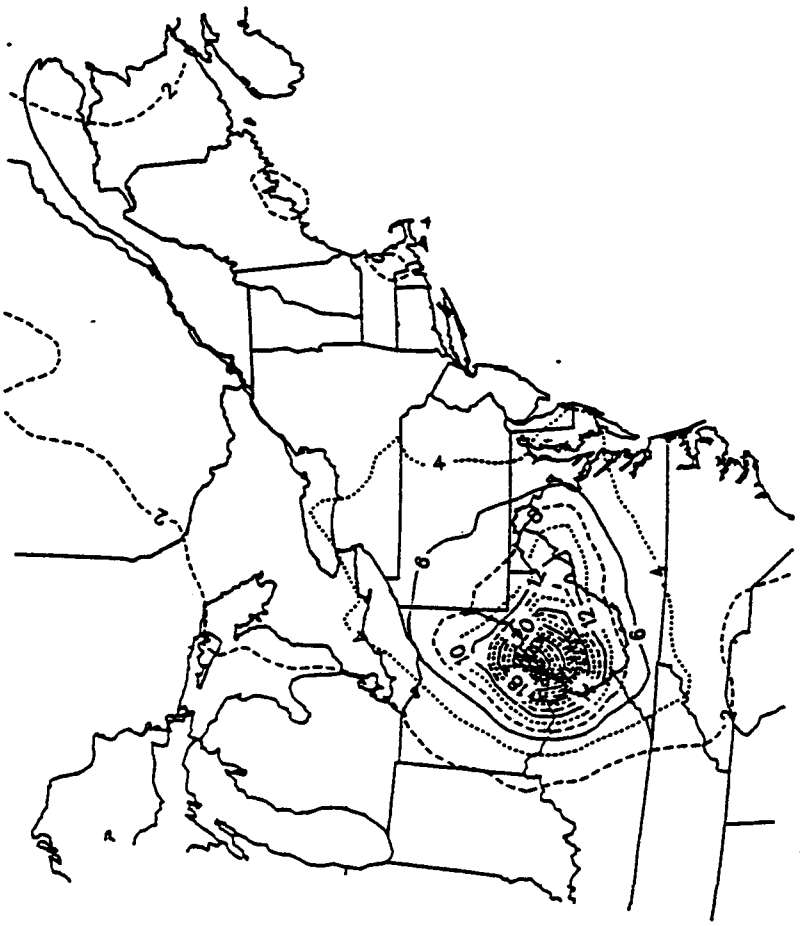
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 19, WESTERN VA/EASTERN WV



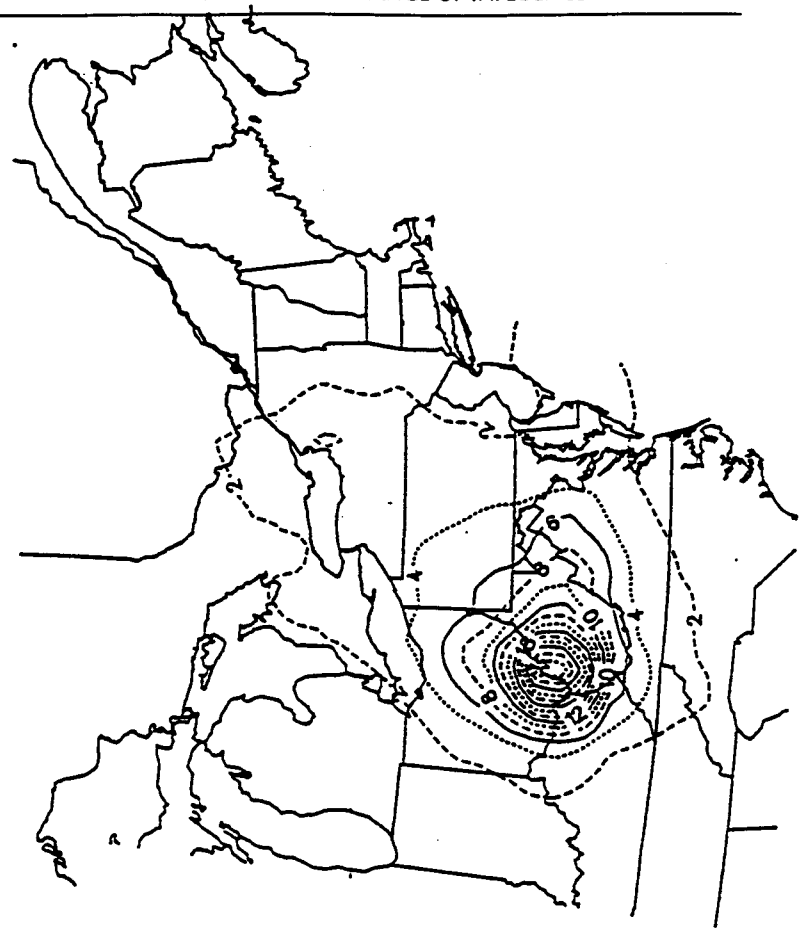
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 19, WESTERN VA/EASTERN WV



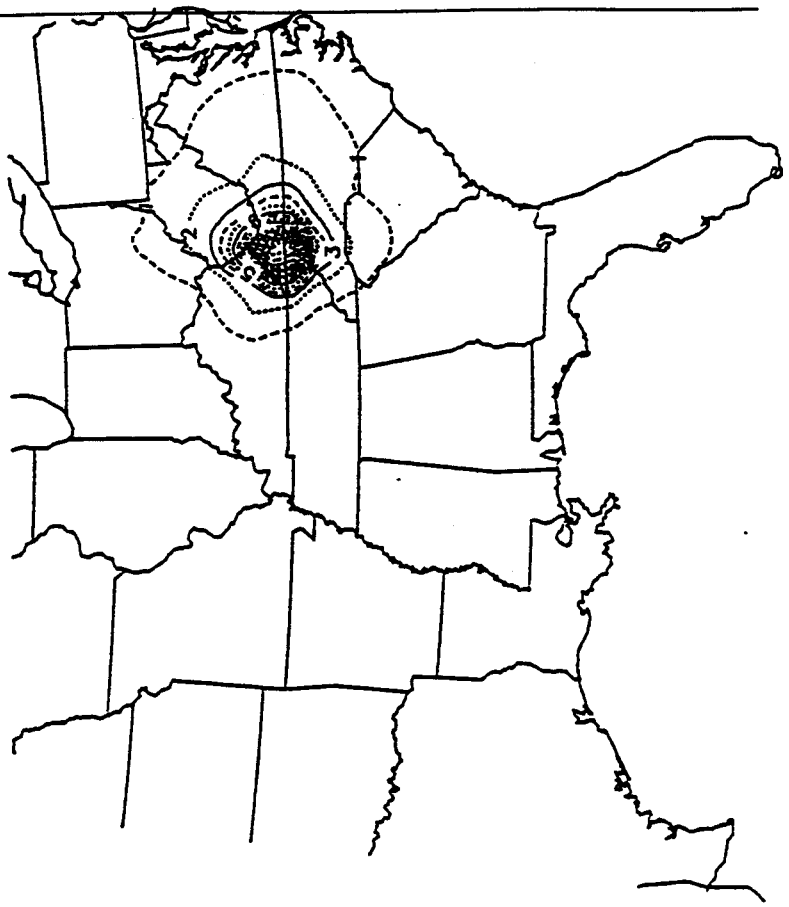
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 20, OH/WV/KY BORDER



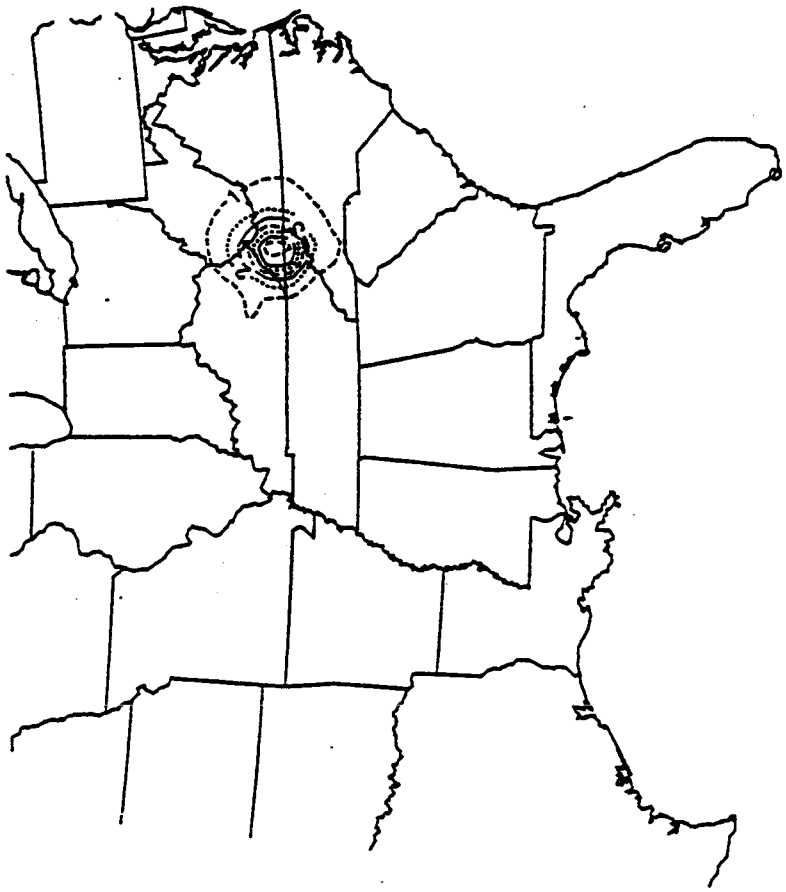
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 20, OH/WV/KY BORDER



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 21, KY/WV/VA BORDER



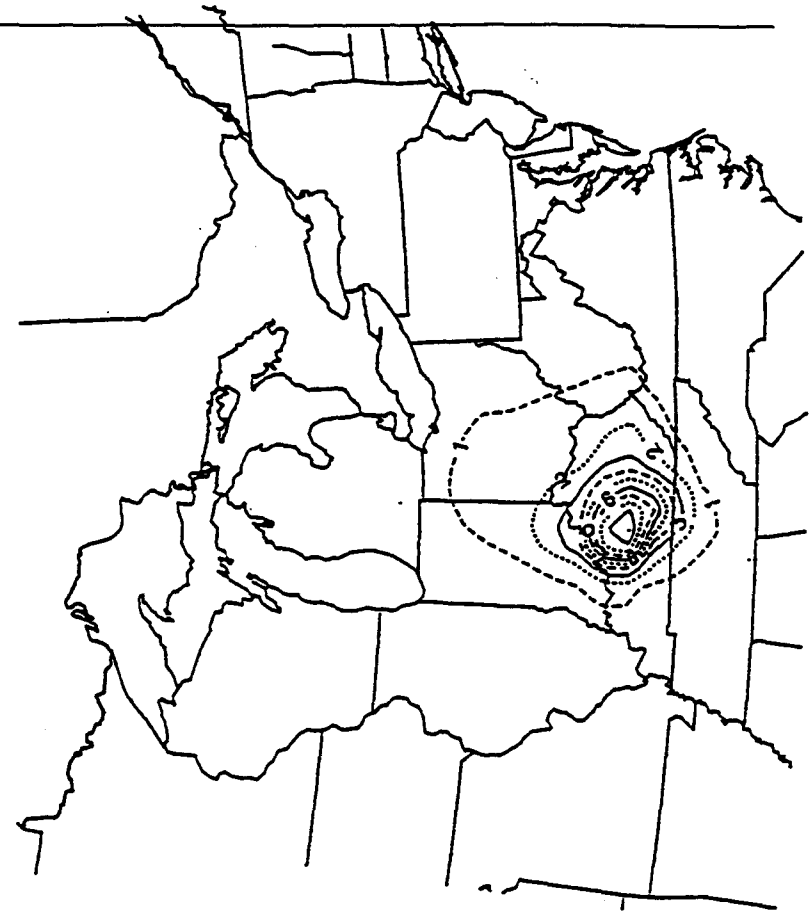
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 21, KY/WV/VA BORDER



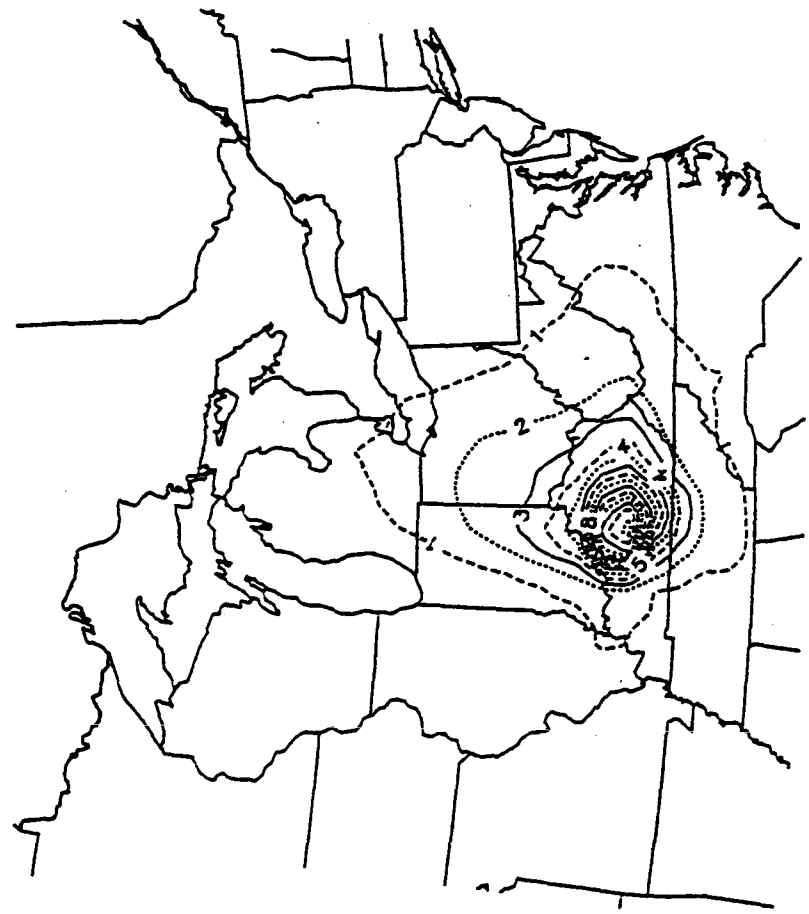
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 22, CINCINNATI AREA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 22, CINCINNATI AREA

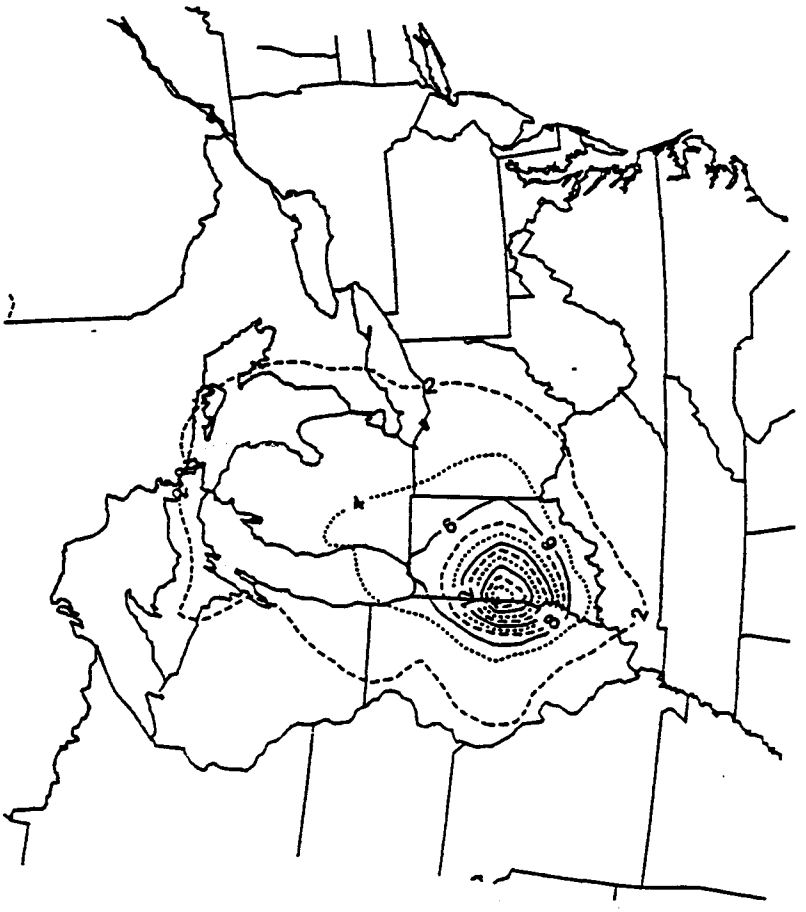
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 23, CENTRAL KY



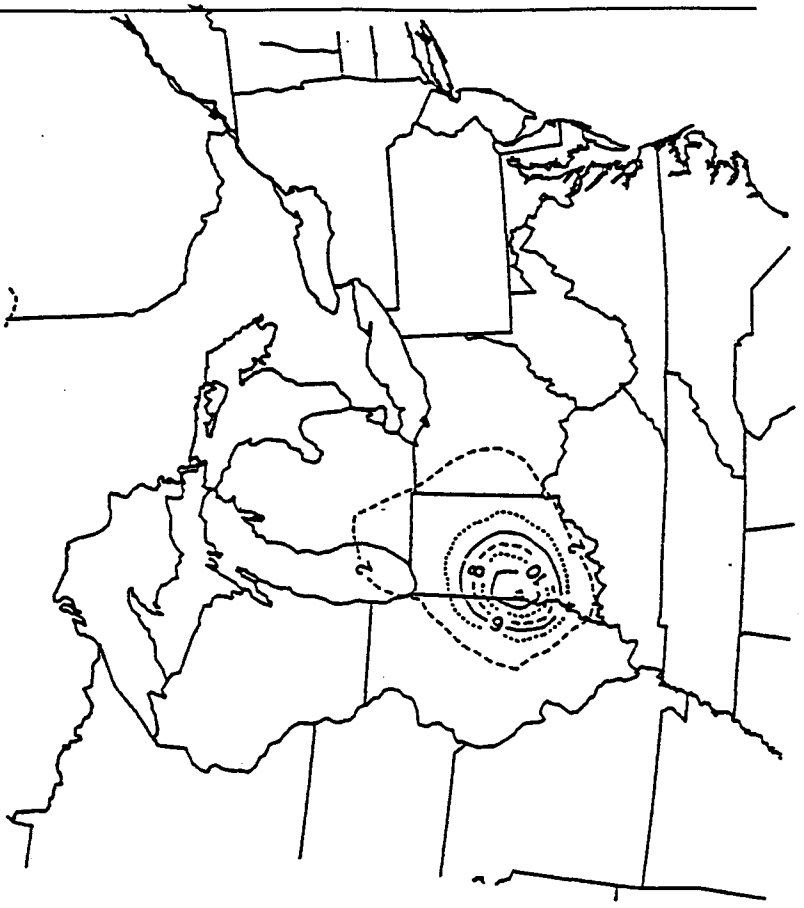
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 23, CENTRAL KY



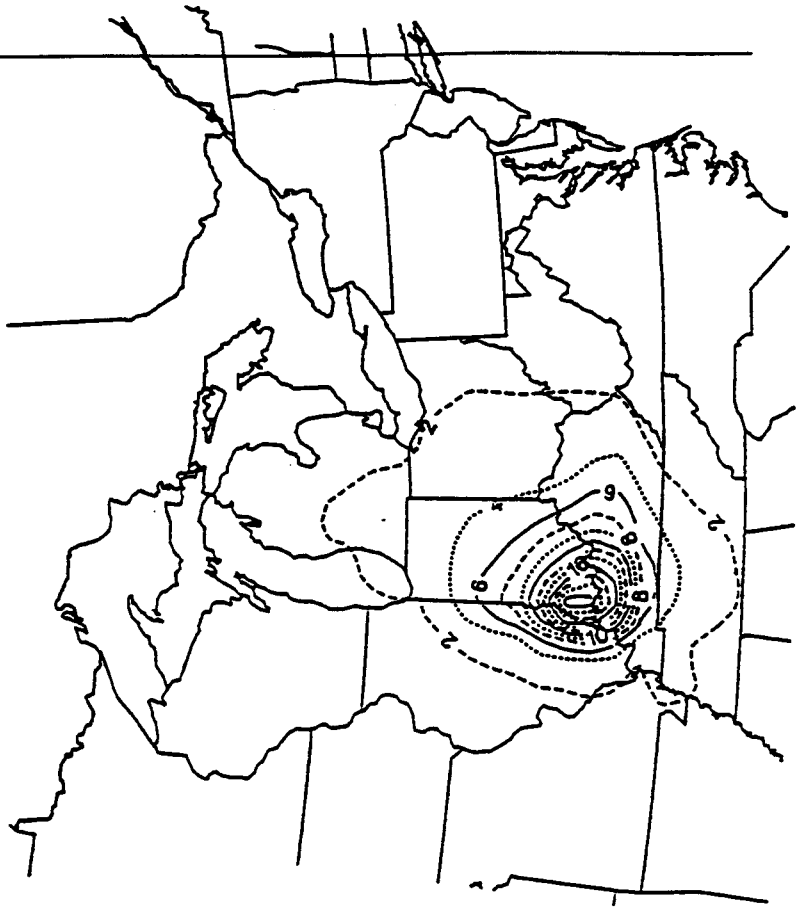
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 24, CENTRAL IL/IN BORDER



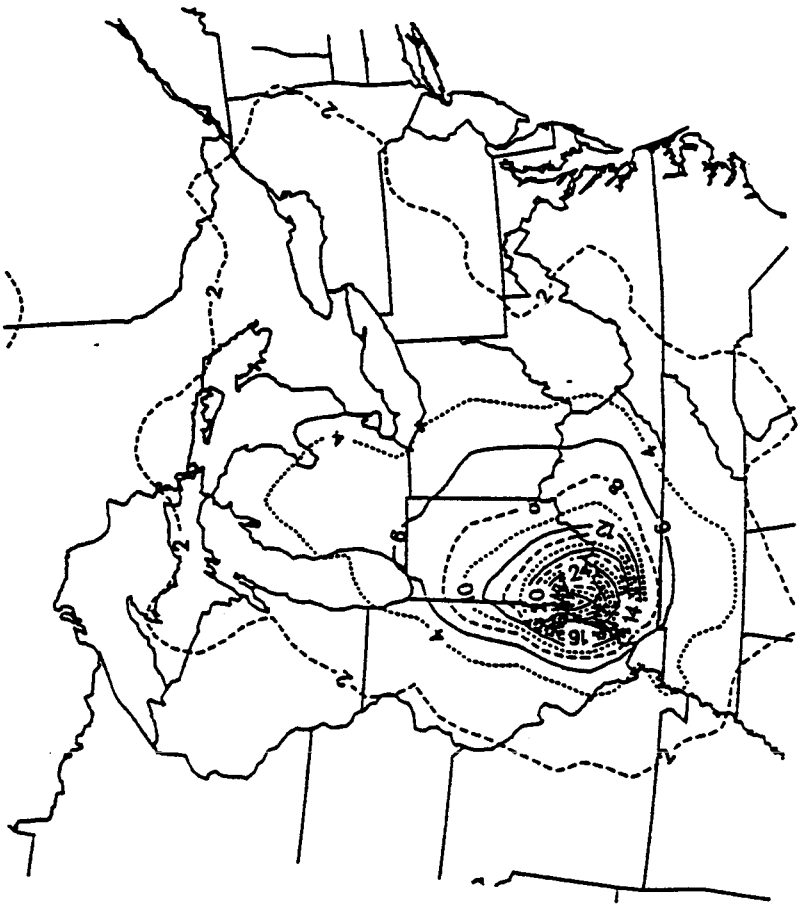
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 24, CENTRAL IL/IN BORDER



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 25, SOUTHWEST IN/KY BORDER

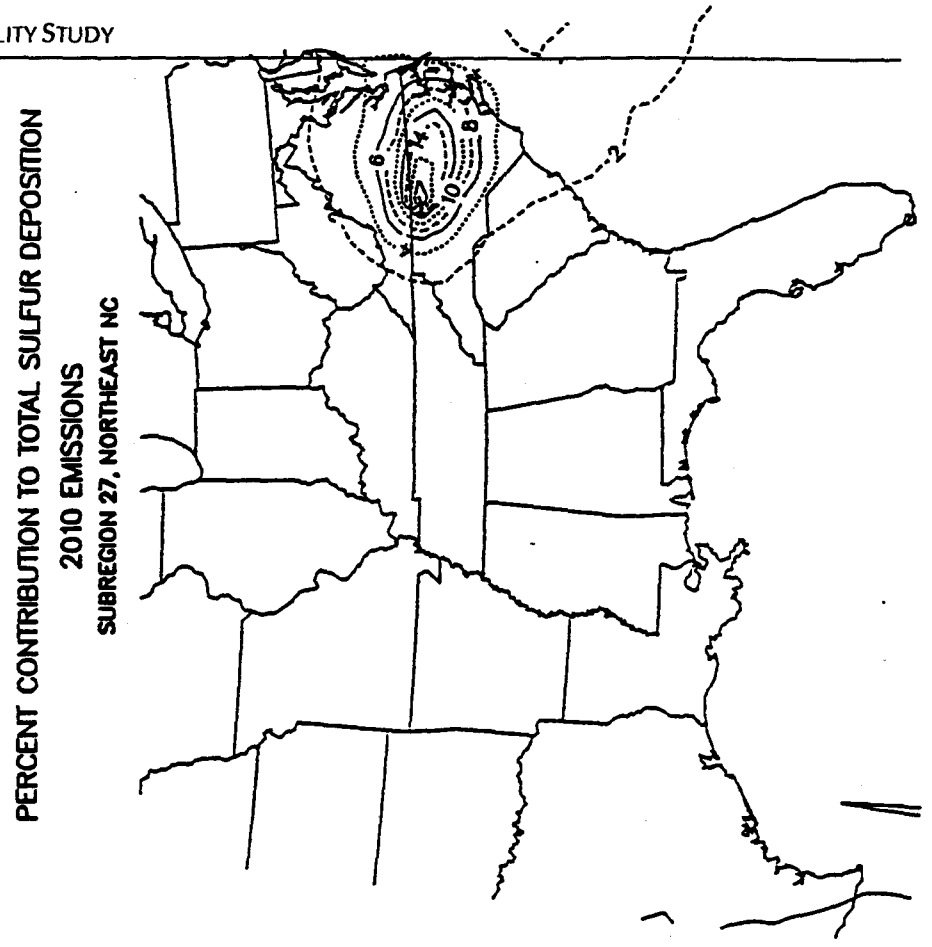


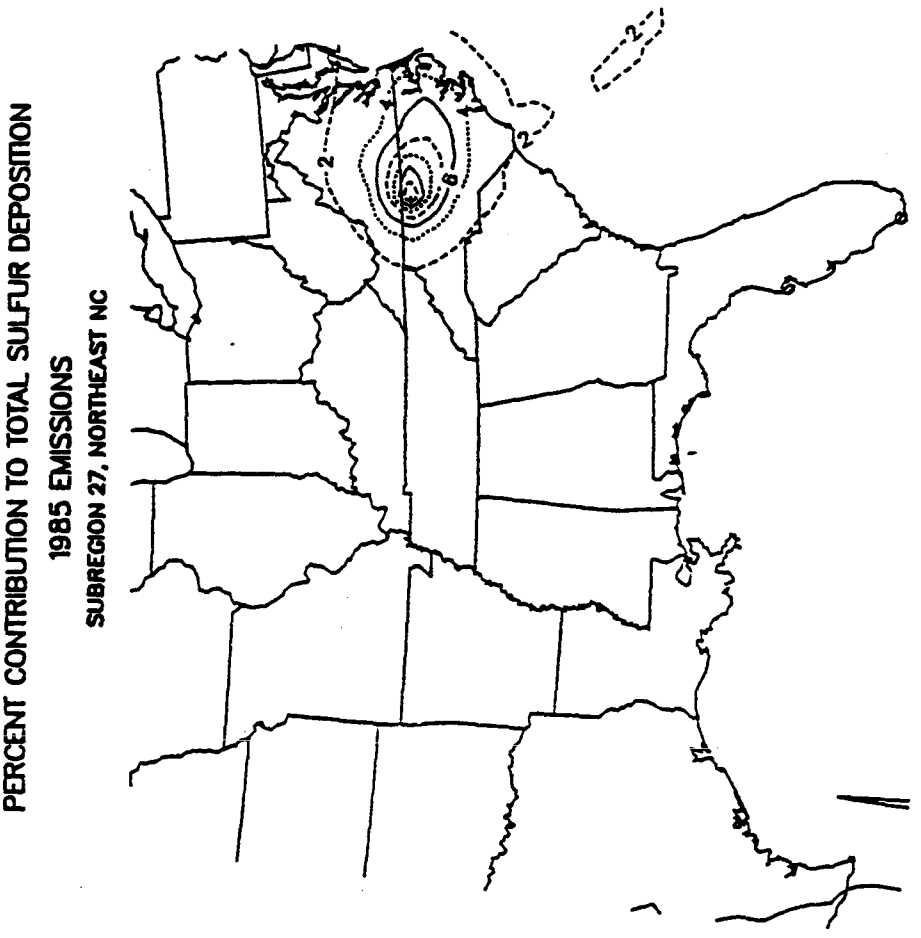
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 25, SOUTHWEST IN/KY BORDER

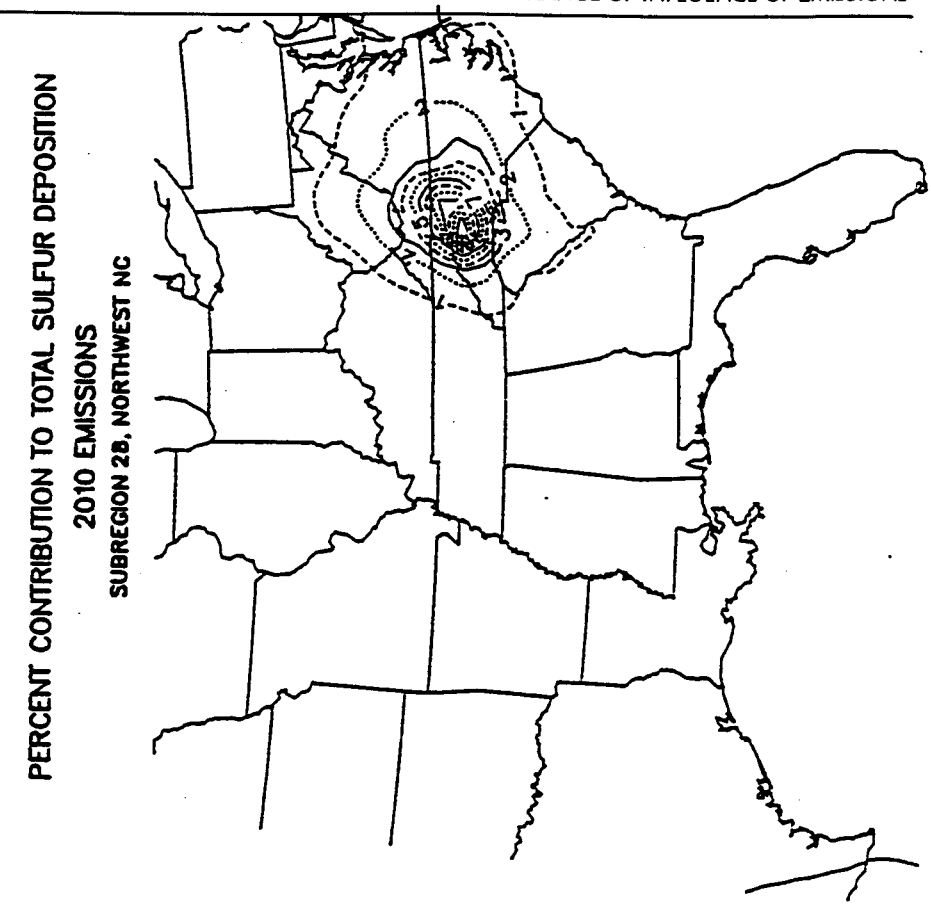


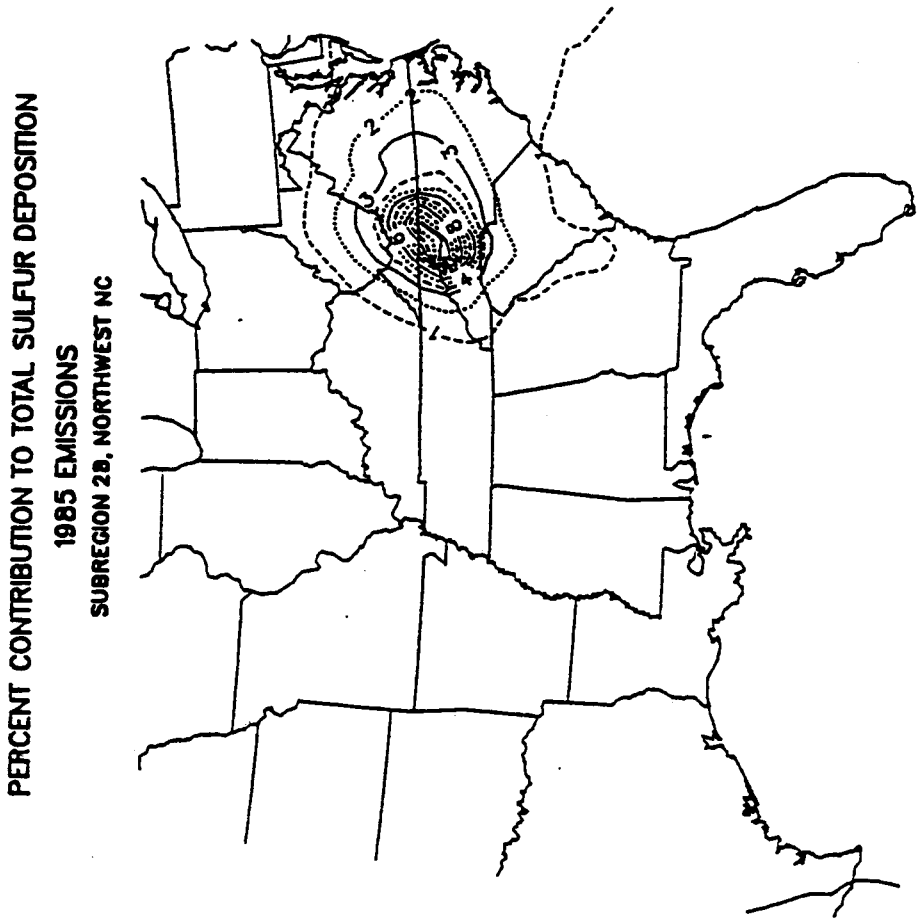
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 26, ST LOUIS AREA

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 26, ST LOUIS AREA

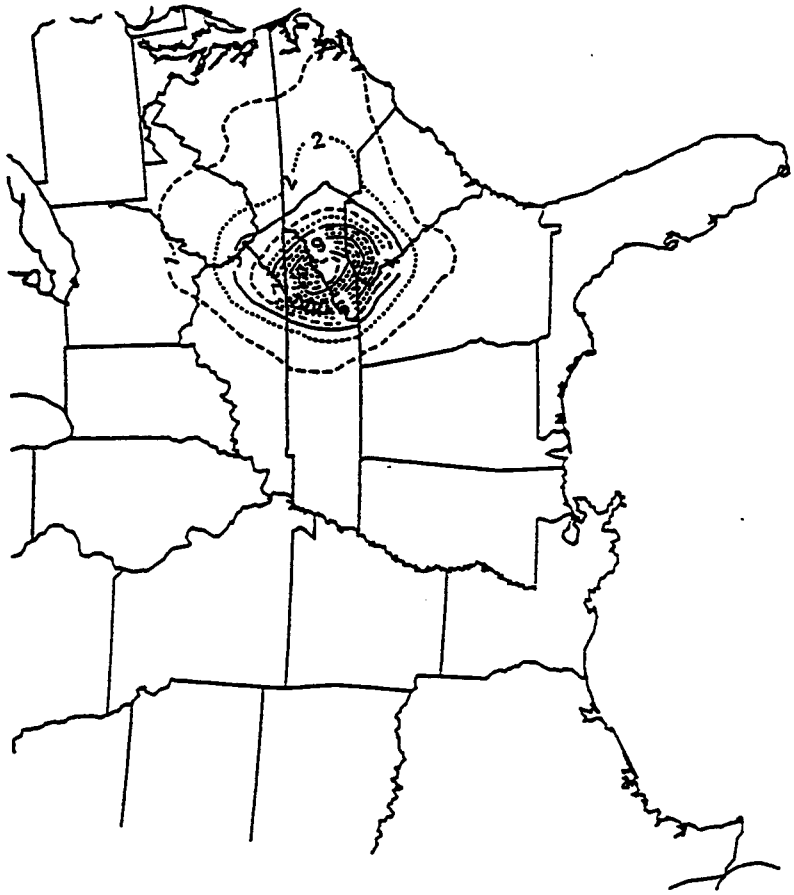

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 27, NORTHEAST NC
2
6
8
10


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 27, NORTHEAST NC
2
2
6

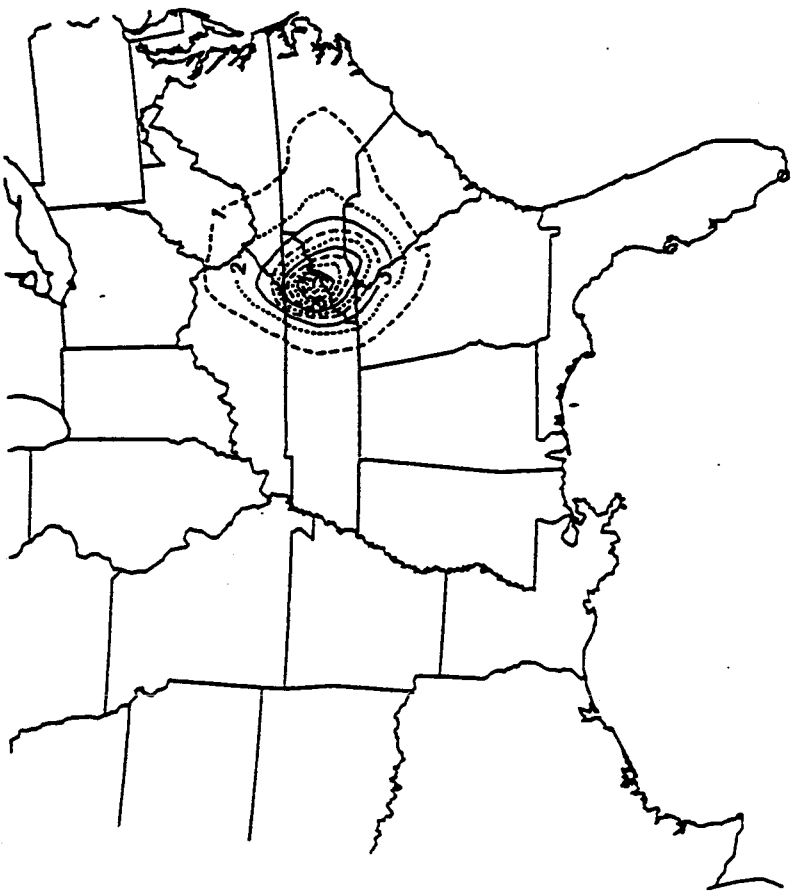

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 28, NORTHWEST NC


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 28, NORTHWEST NC

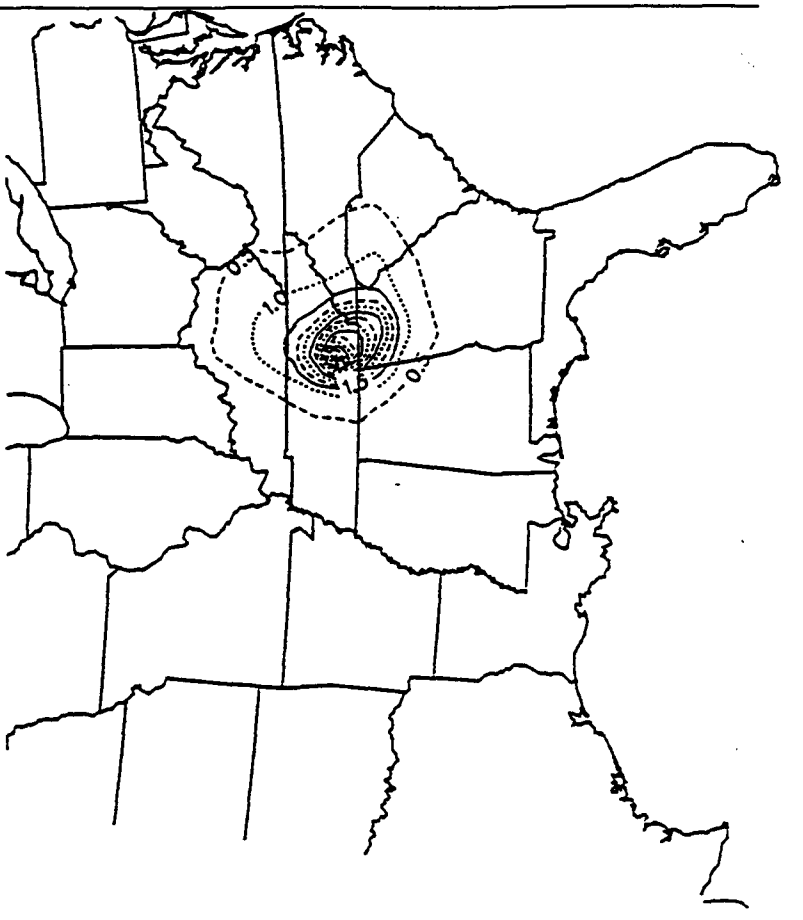
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 29, BLUE RIDGE AREA



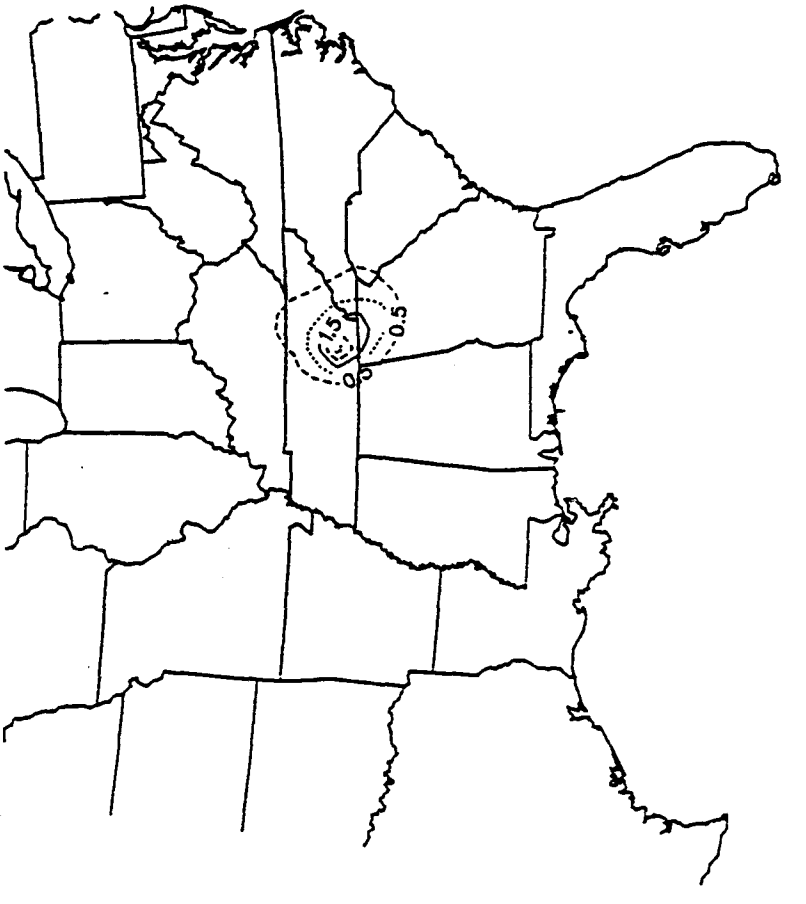
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 29, BLUE RIDGE AREA

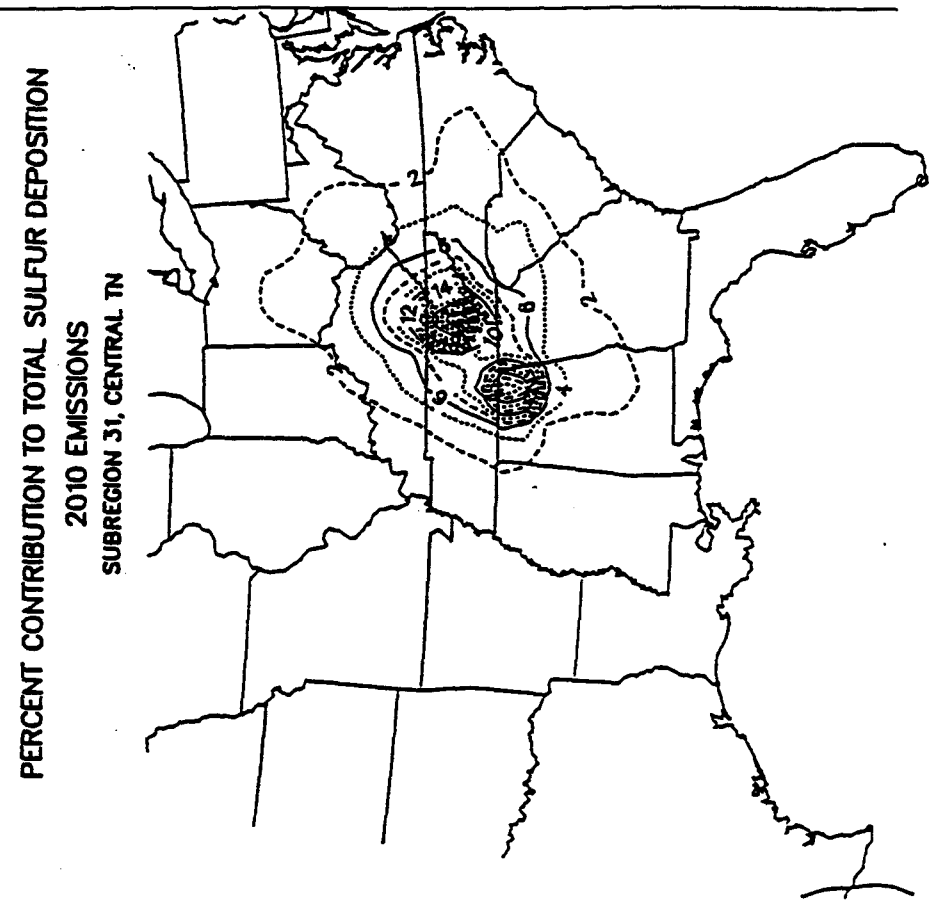


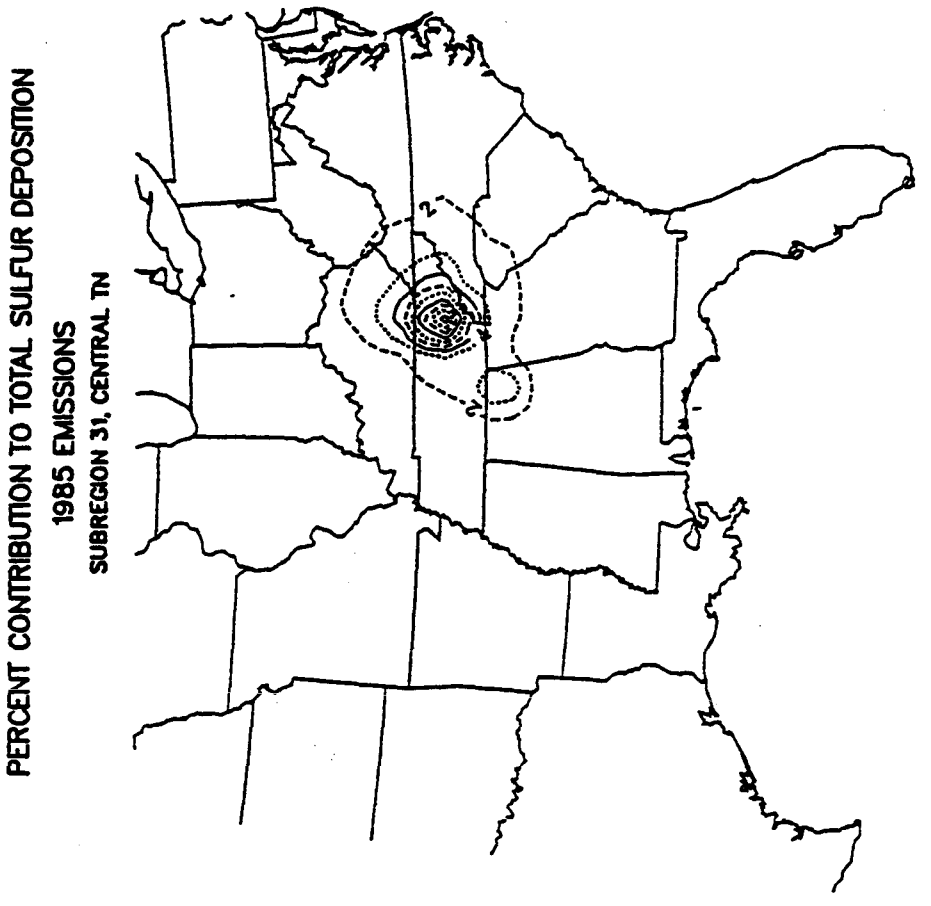
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 30, NC/TN/GA BORDER

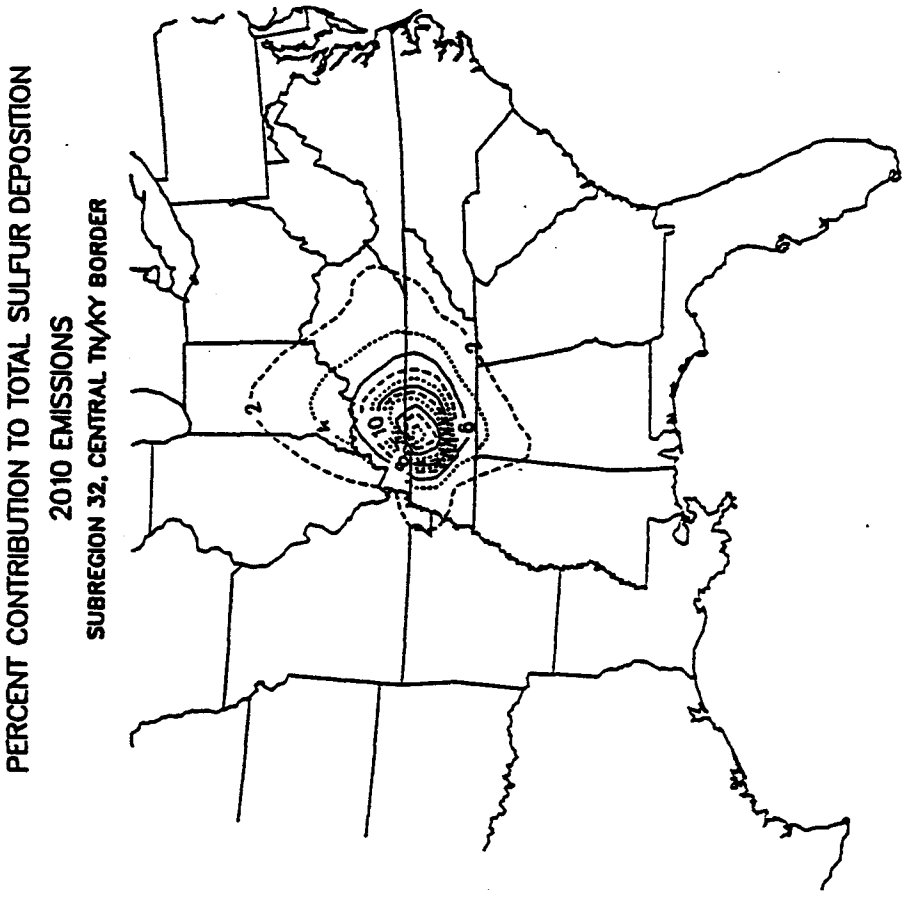


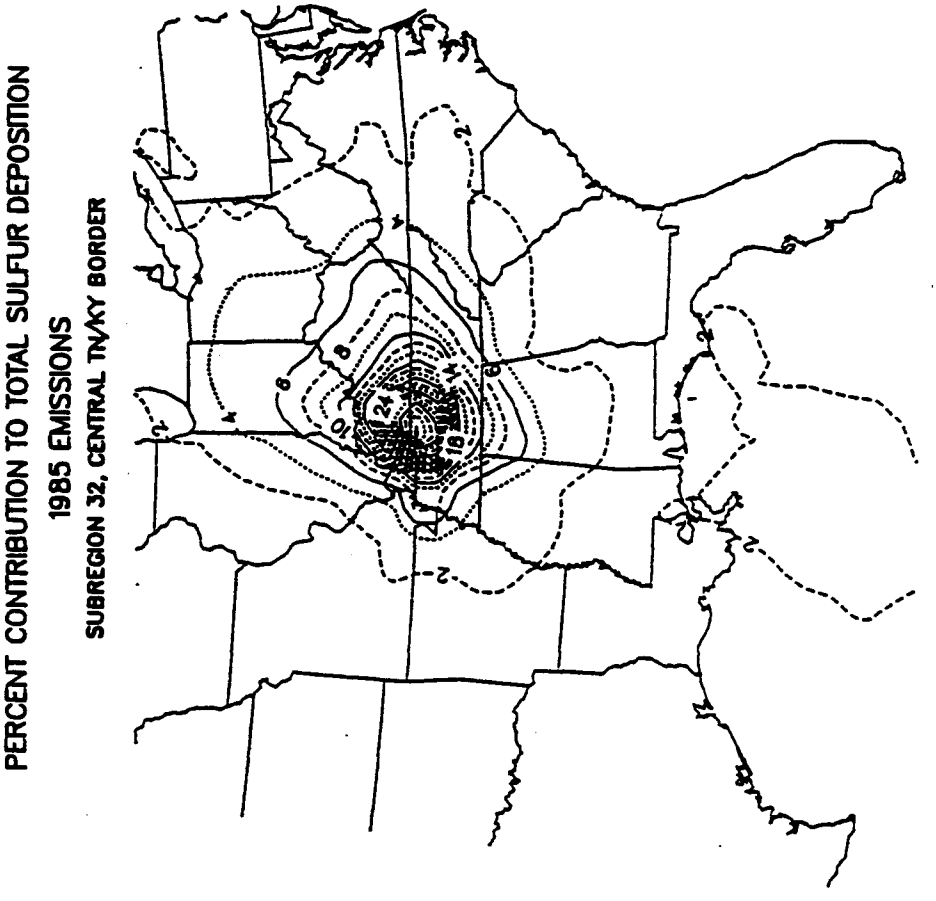
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 30, NC/TN/GA BORDER

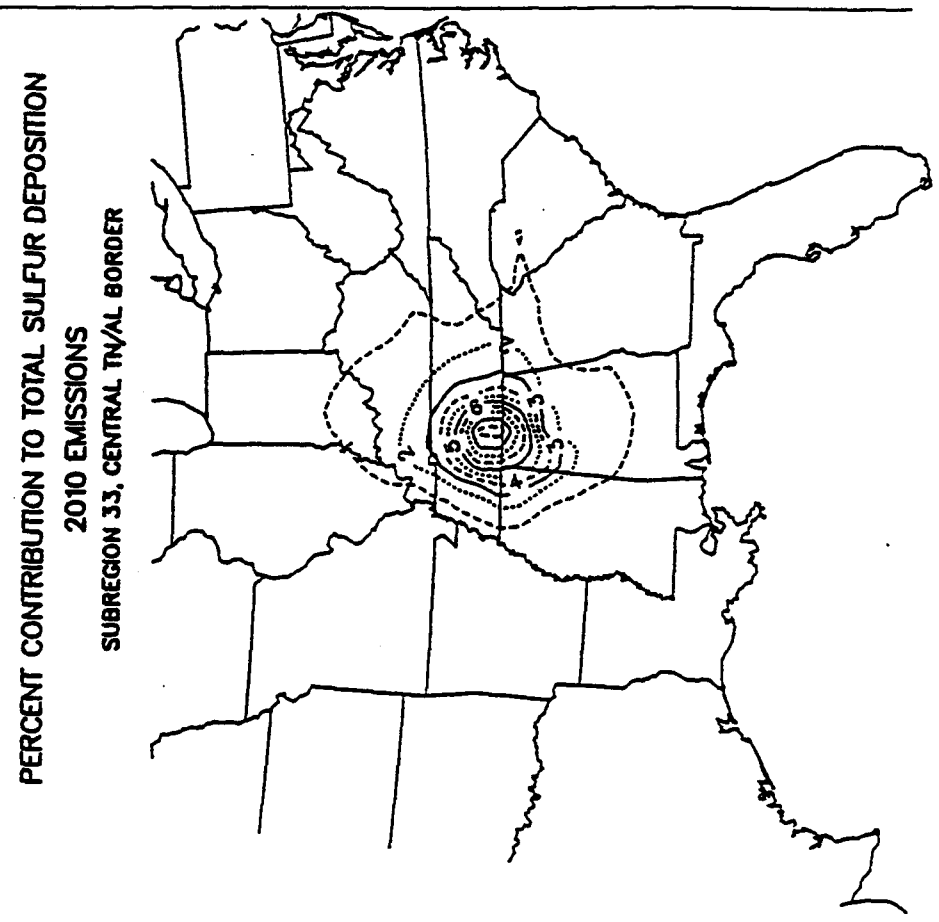


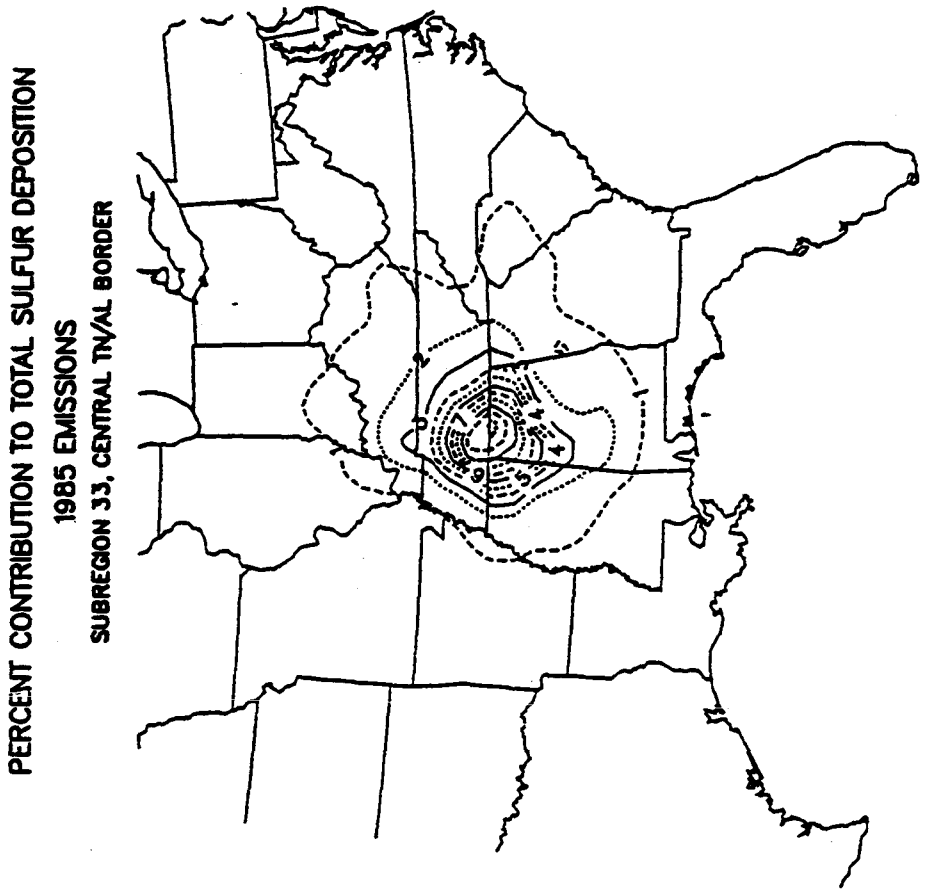

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 31, CENTRAL TN
2
2
4
6
8
10
12
14

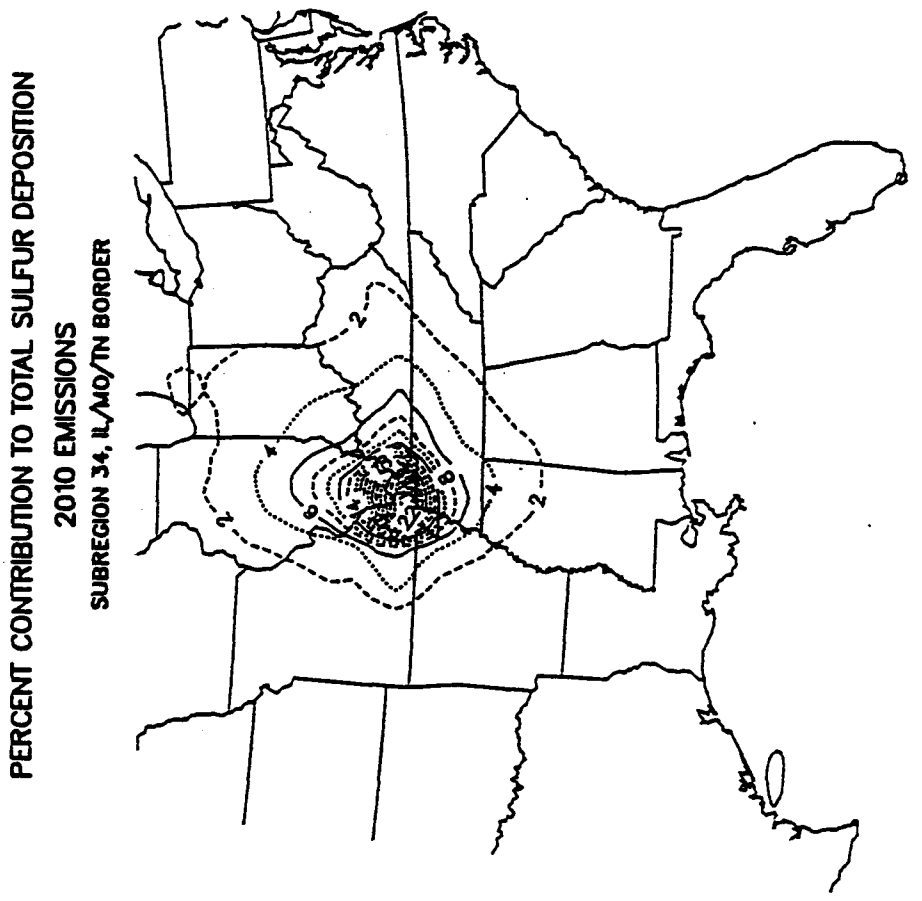

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 31, CENTRAL TN
2
2
4

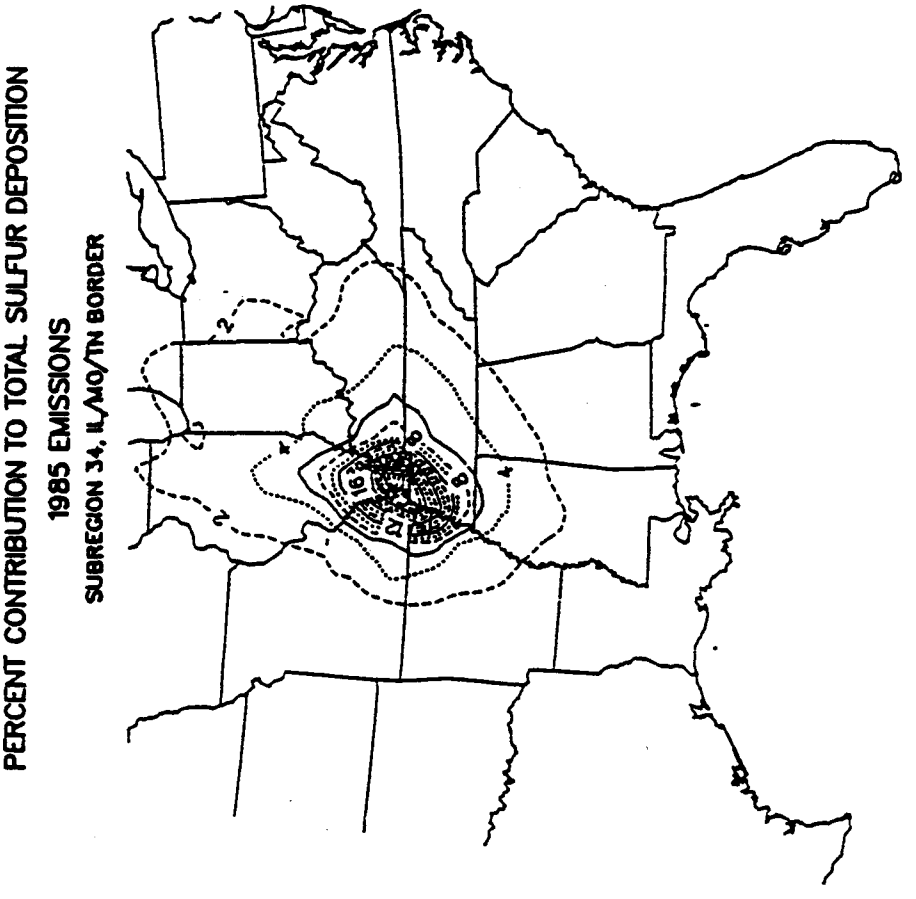

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 32, CENTRAL TN/KY BORDER
2
4
6
8
10


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 32, CENTRAL TN/KY BORDER
2
4
6
8
10
14
18
24

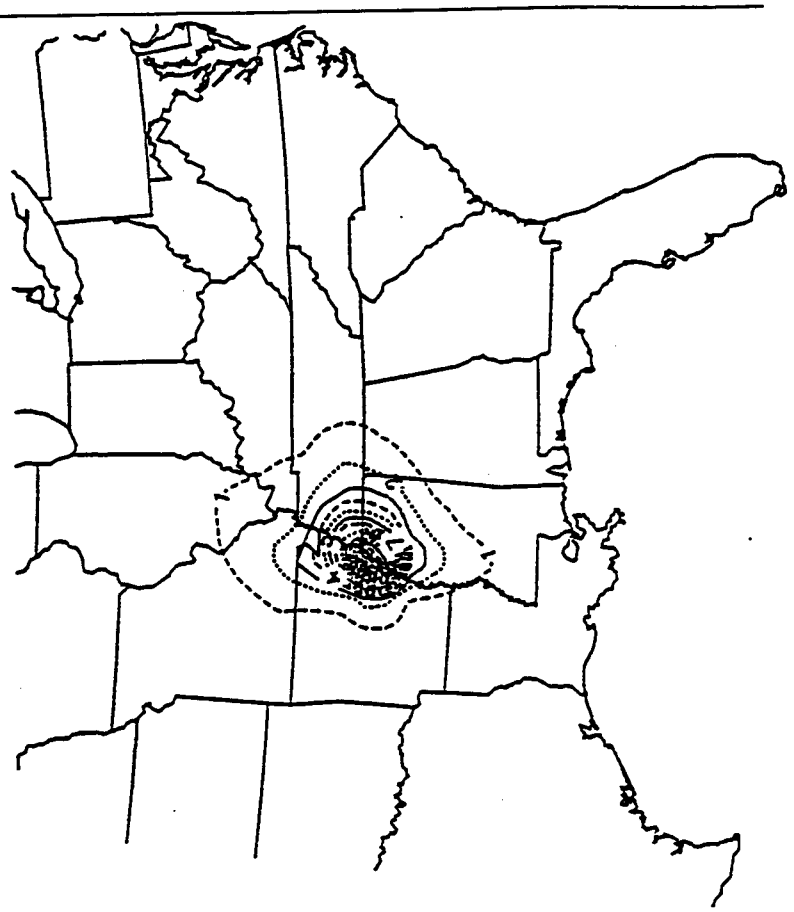

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 33, CENTRAL TN/AL BORDER


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 33, CENTRAL TN/AL BORDER

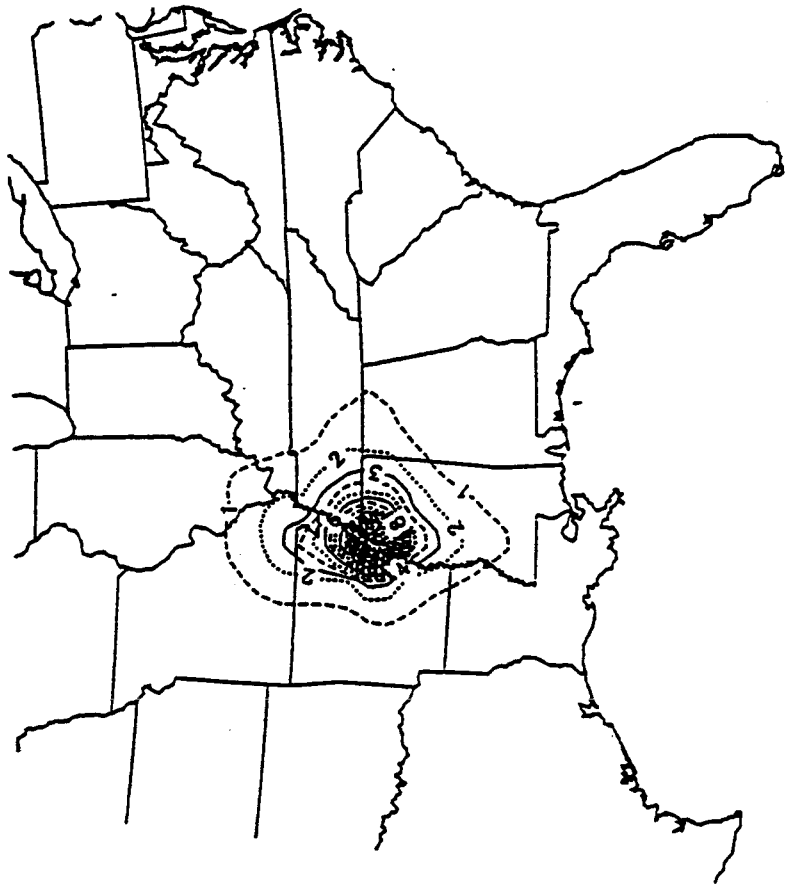

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 34, IL/MO/TN BORDER
2
4
6
2
4
2


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 34, IL/MO/TN BORDER
2
4
6
8
10
12
14
16
2
4

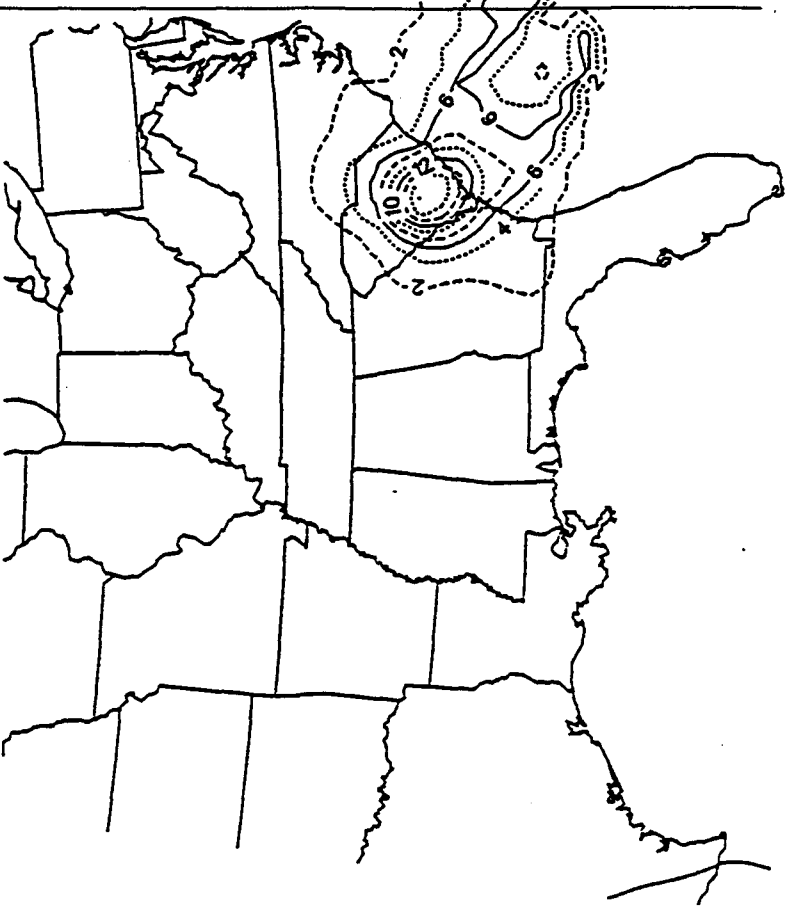
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 35, MEMPHIS AREA



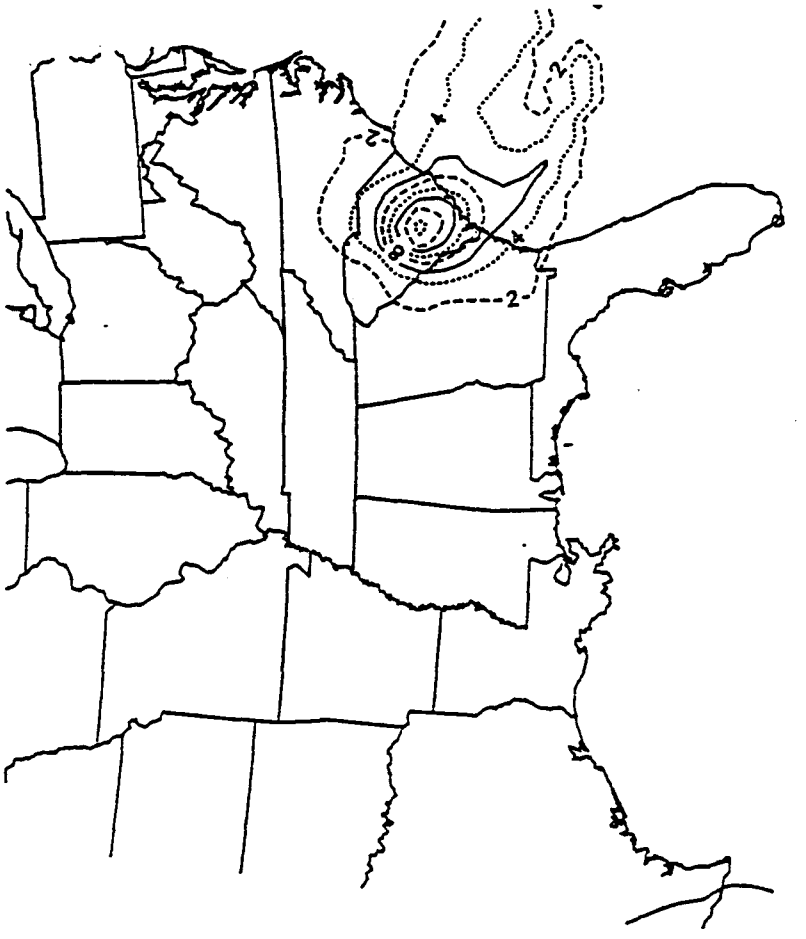
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 35, MEMPHIS AREA



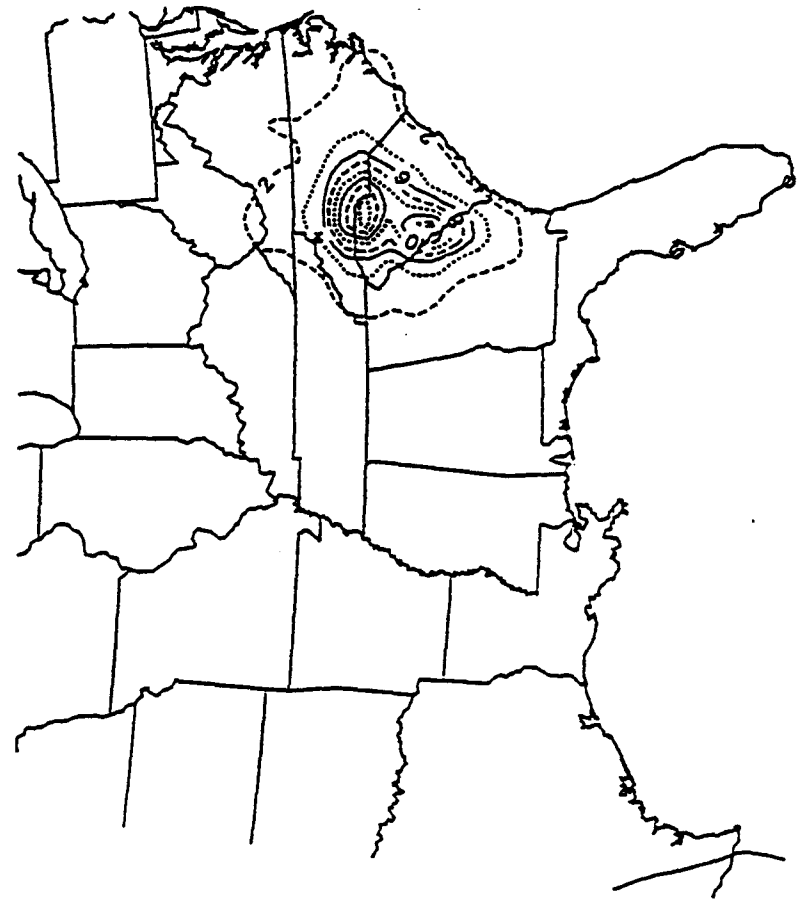
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 36, SOUTHEAST SC



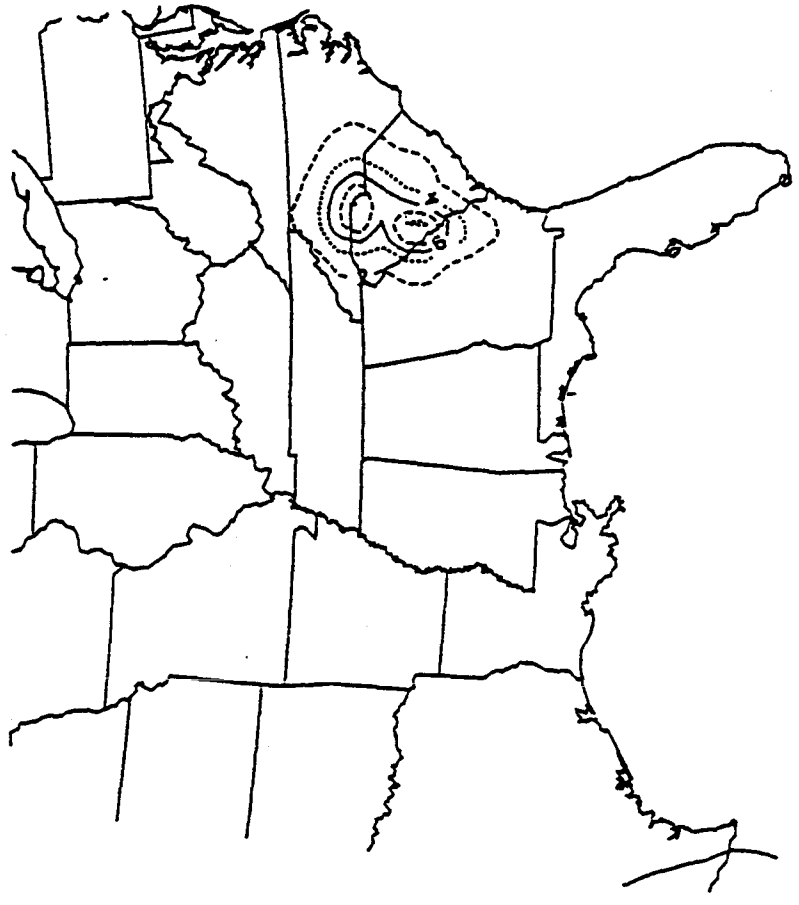
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 36, SOUTHEAST SC



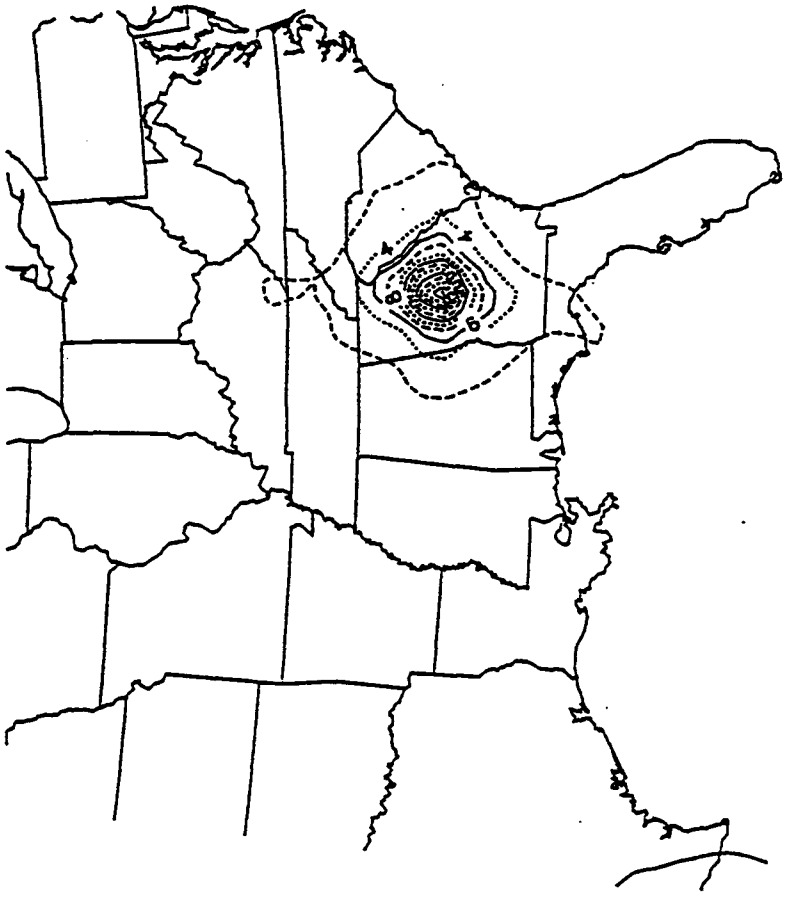
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 37, CENTRAL SC/NC BORDER



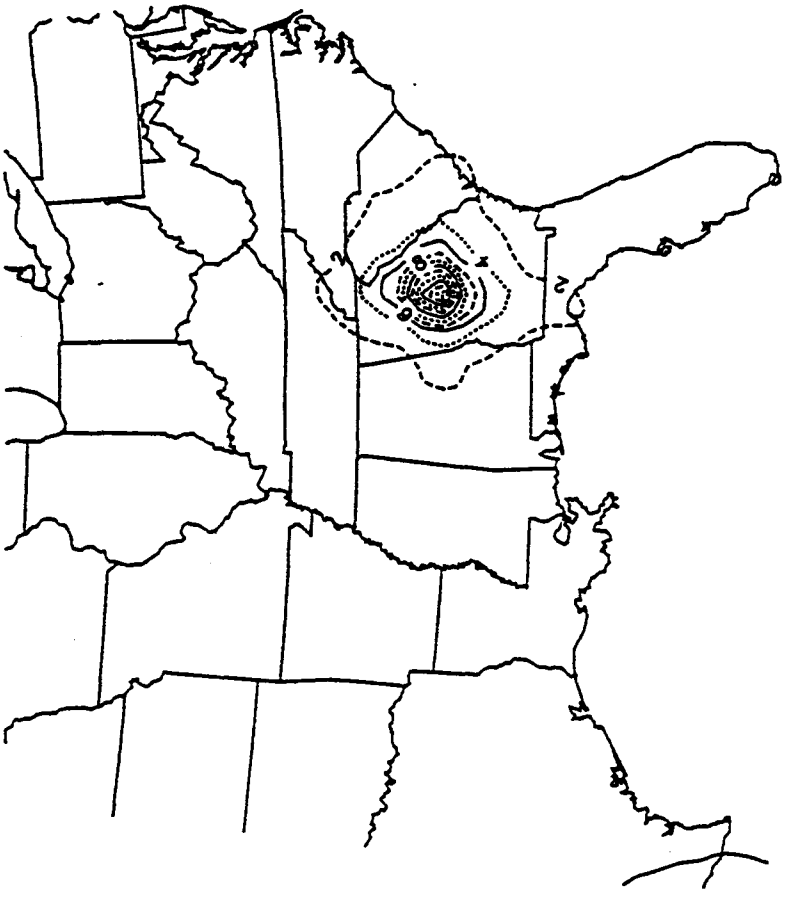
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 37, CENTRAL SC/NC BORDER

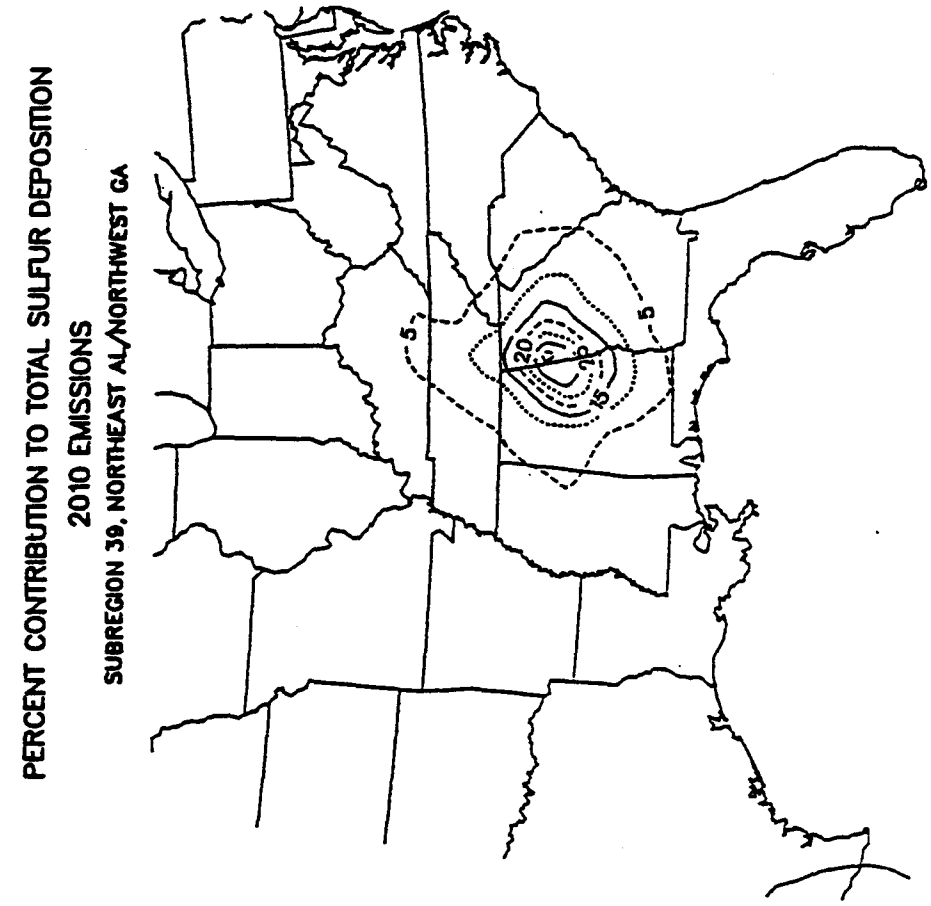


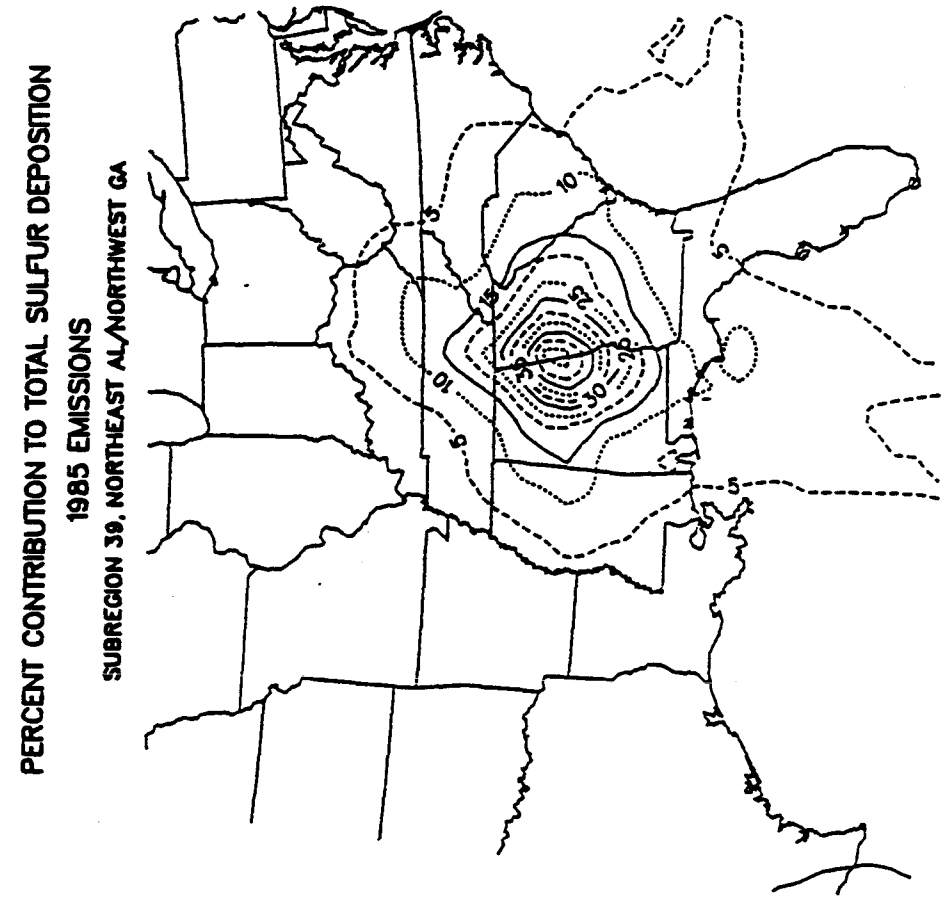
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 38, NORTHEAST GA



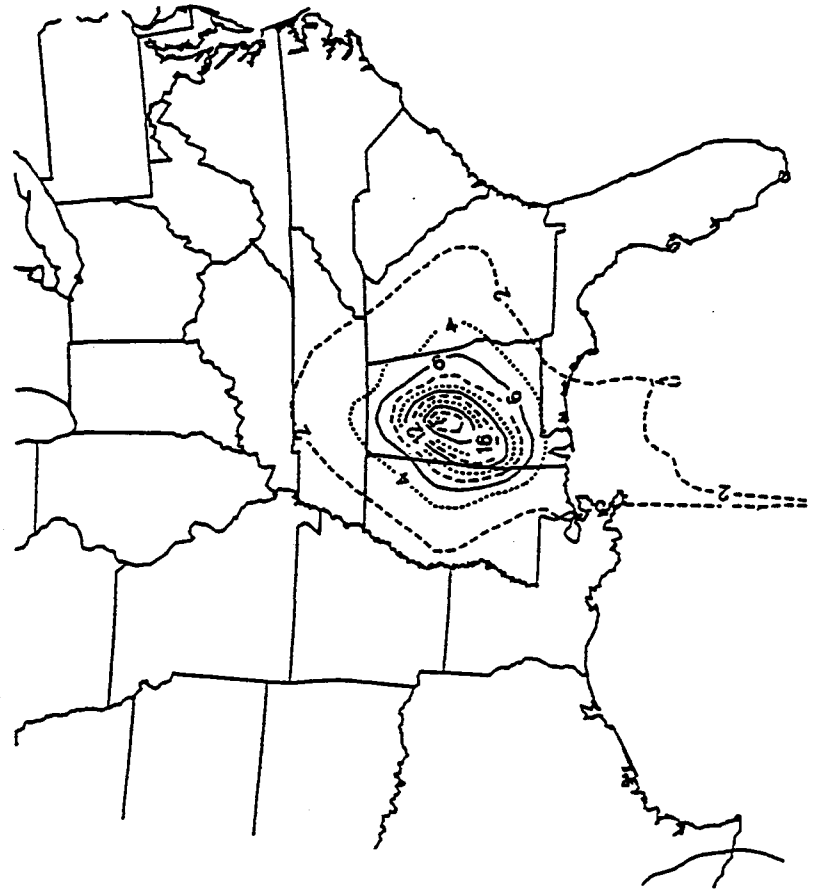
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 38, NORTHEAST GA



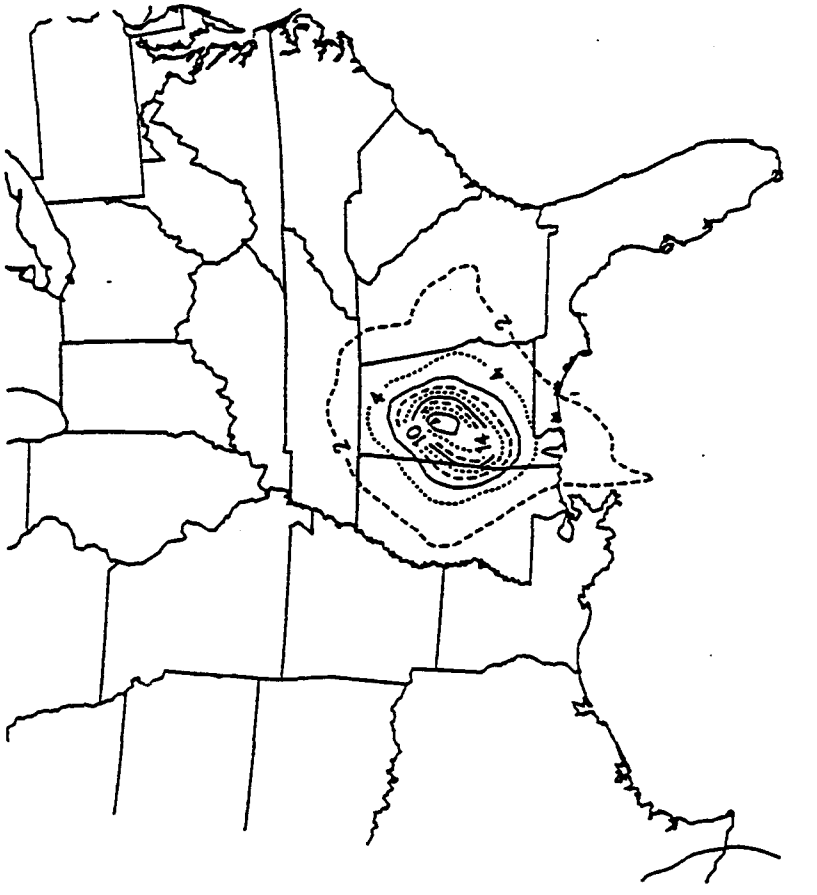

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 39, NORTHEAST AL/NORTHWEST GA
5
5
5
20
15
10
N


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 39, NORTHEAST AL/NORTHWEST GA
5
10
5
15
25
20
30
10
5
5
N

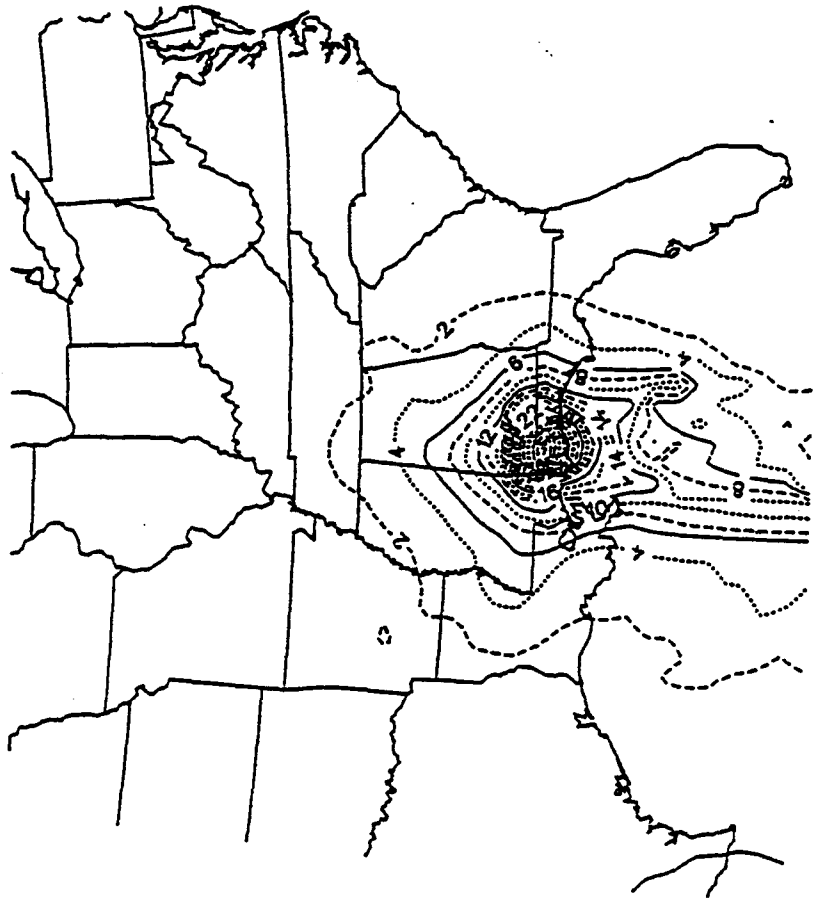
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 40, WESTERN AL



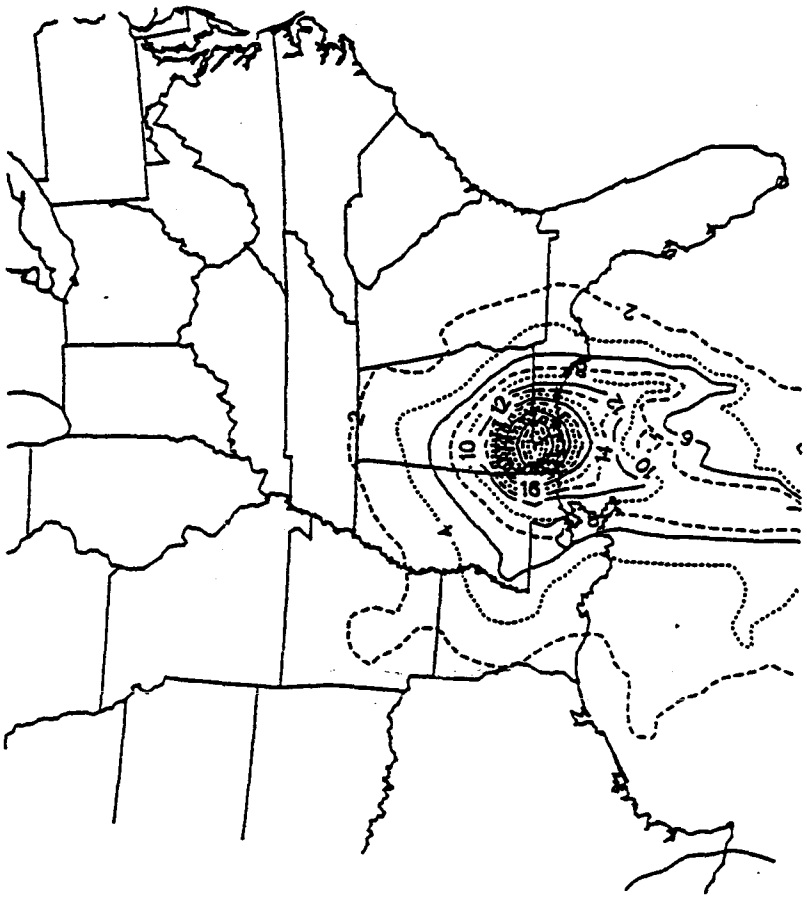
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 40, WESTERN AL



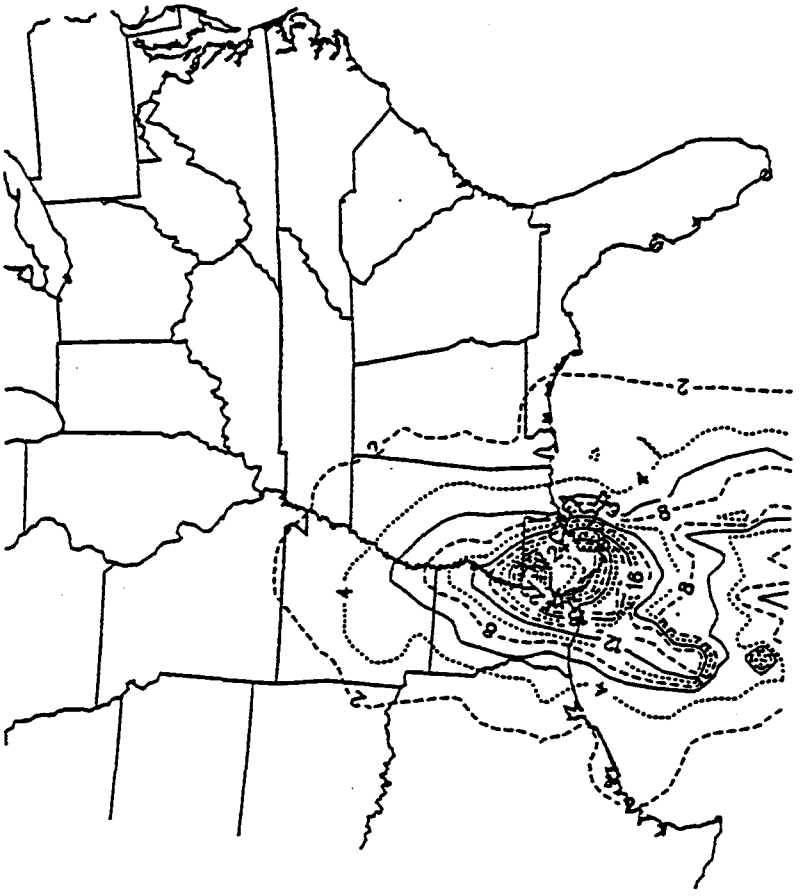
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 41, MOBILE AREA



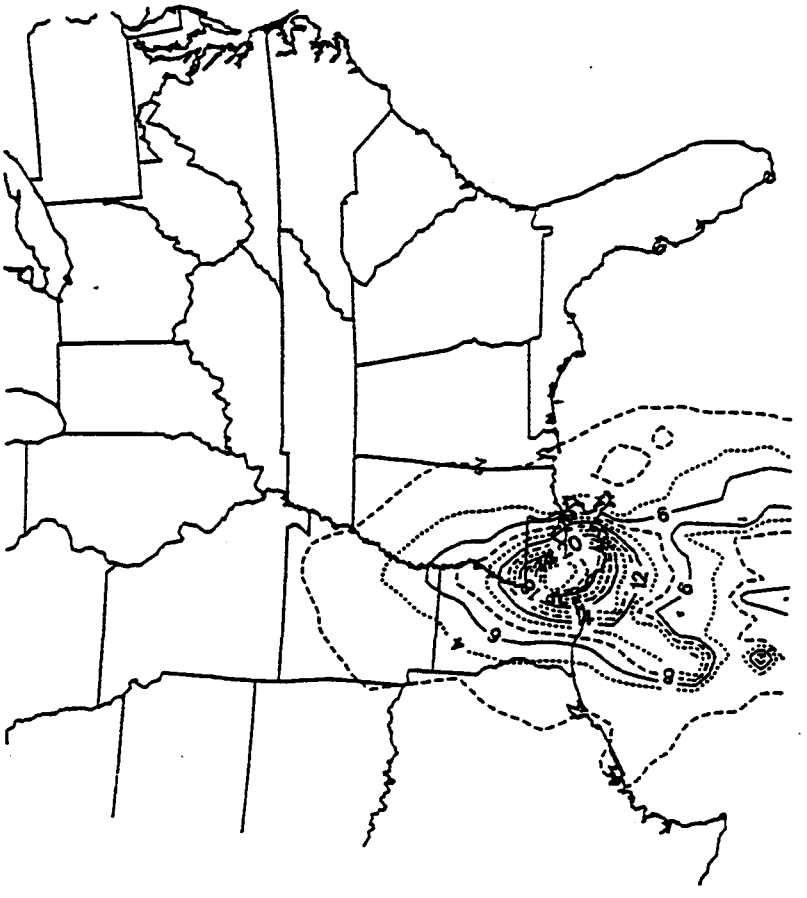
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 41, MOBILE AREA



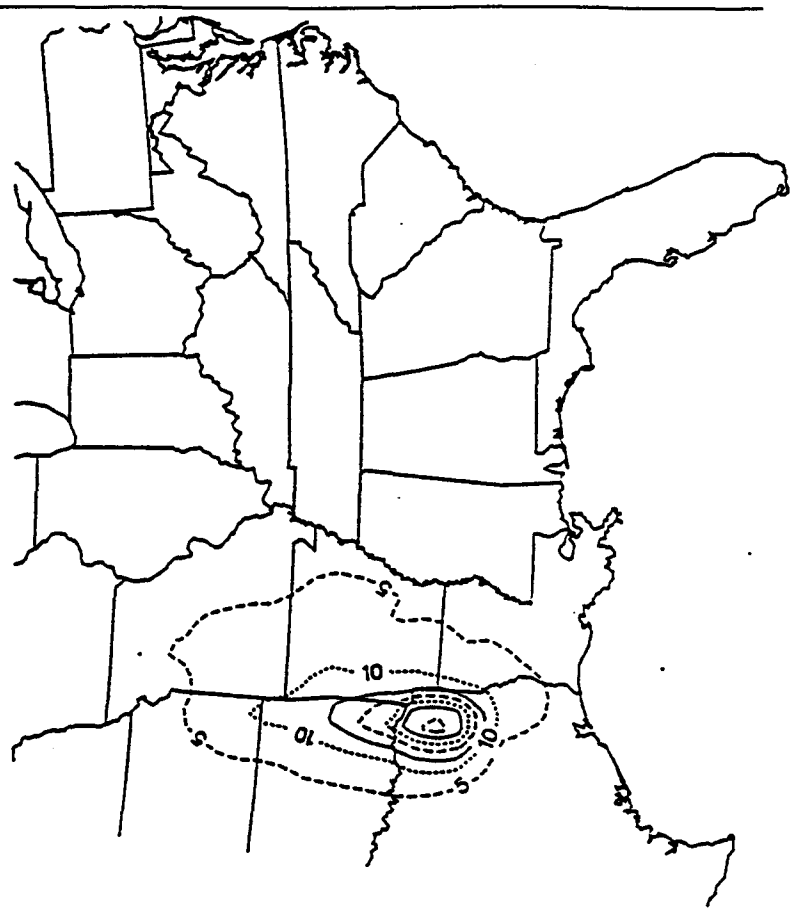
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 42, BATON ROUGE AREA



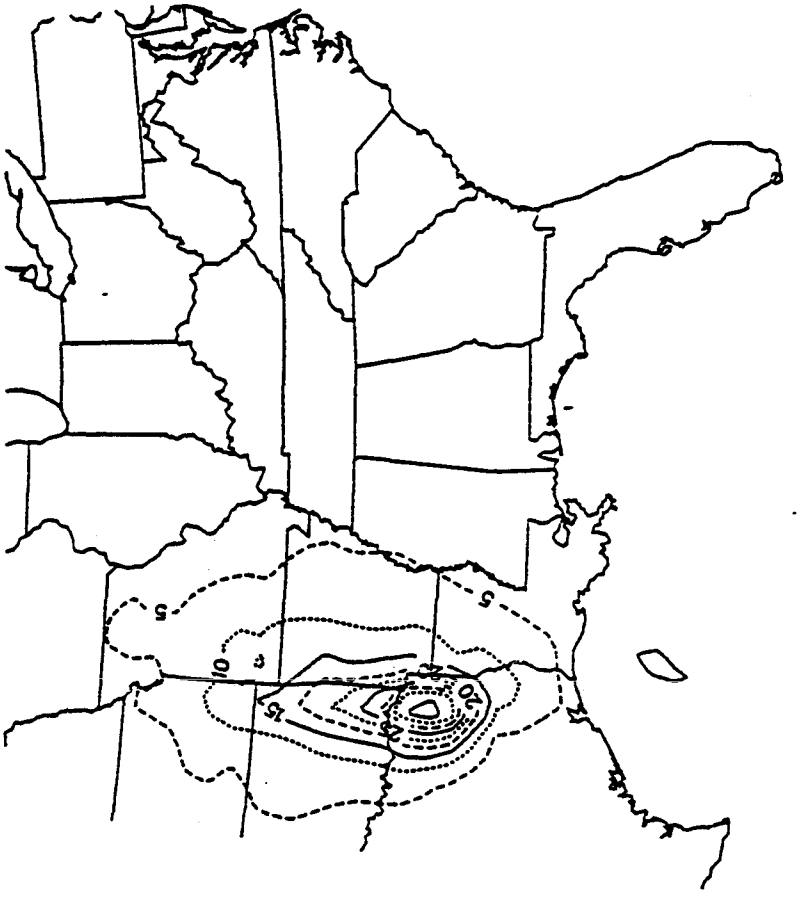
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 42, BATON ROUGE AREA



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 43, NORTHEAST TX



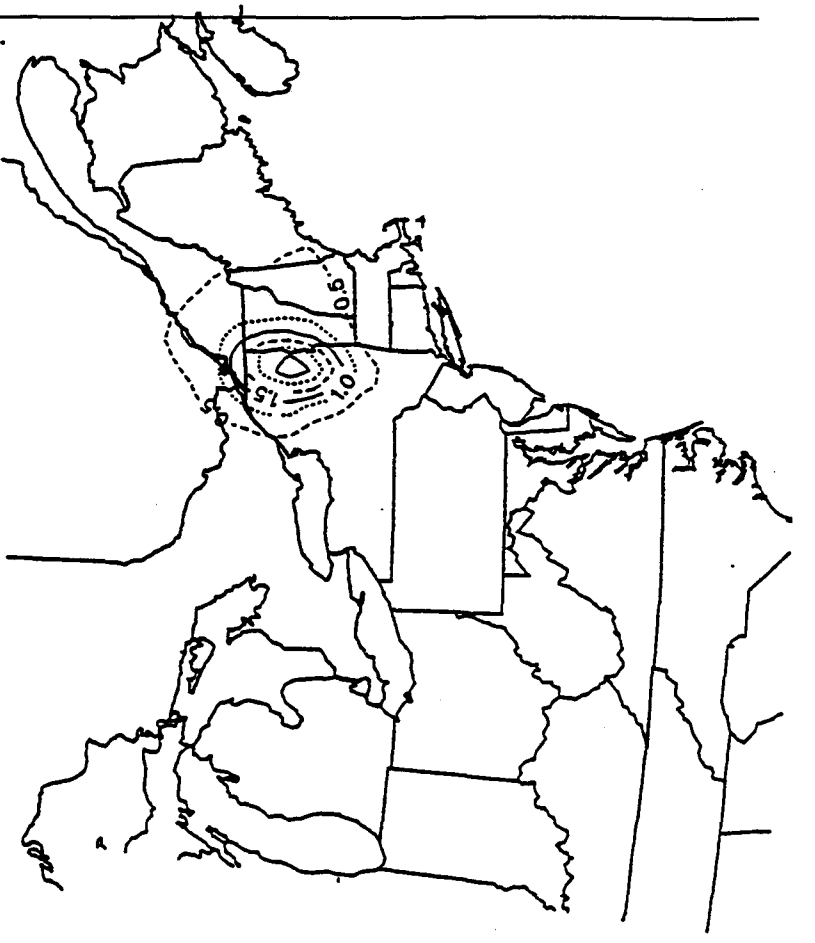
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 43, NORTHEAST TX



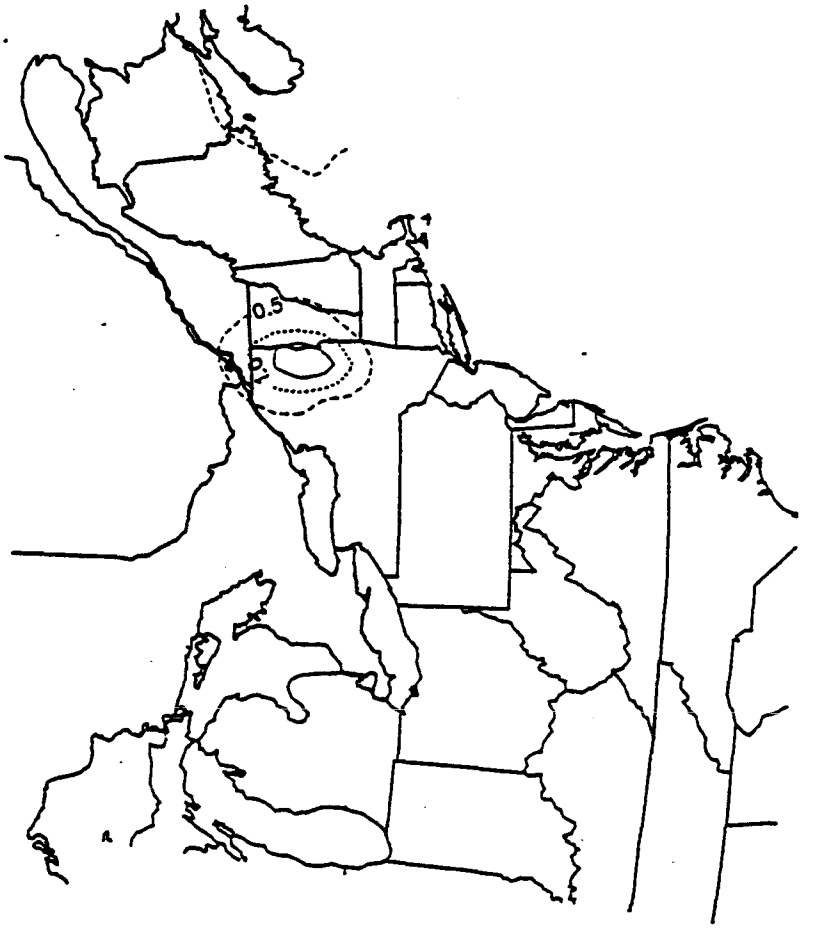
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 44, LAKE ONTARIO/NY SHORE

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 44, LAKE ONTARIO/NY SHORE

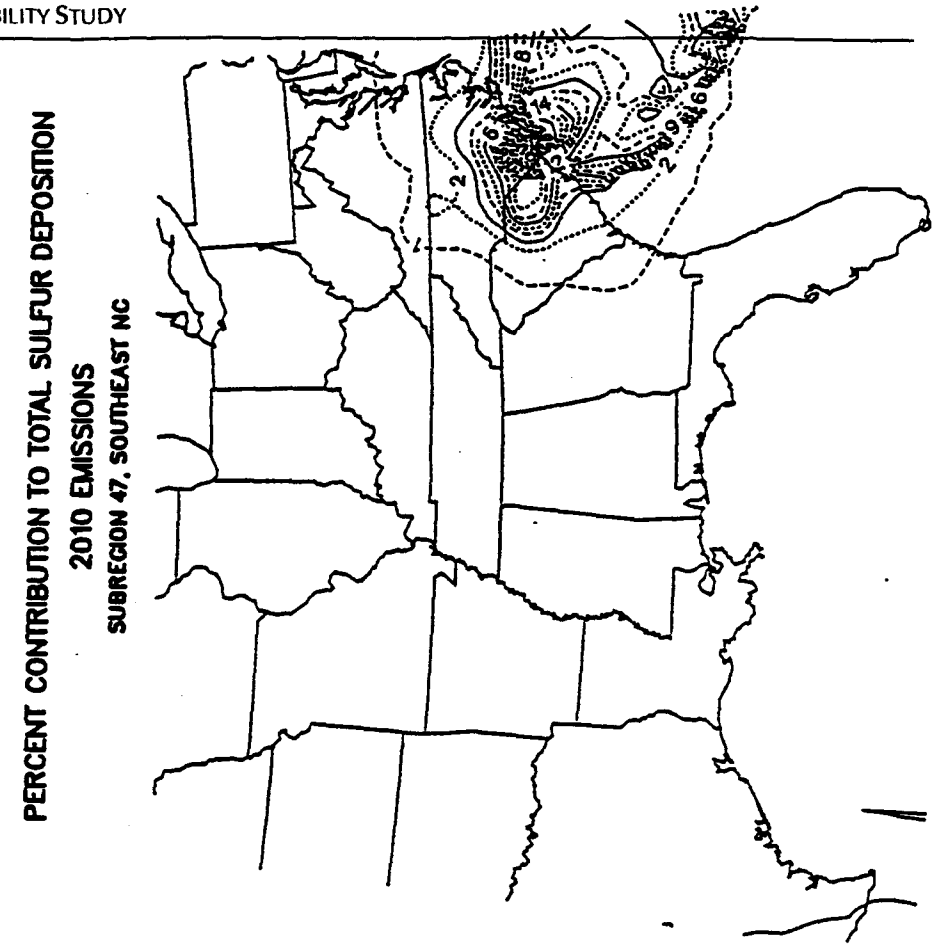
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 45, ADIRONDACKS

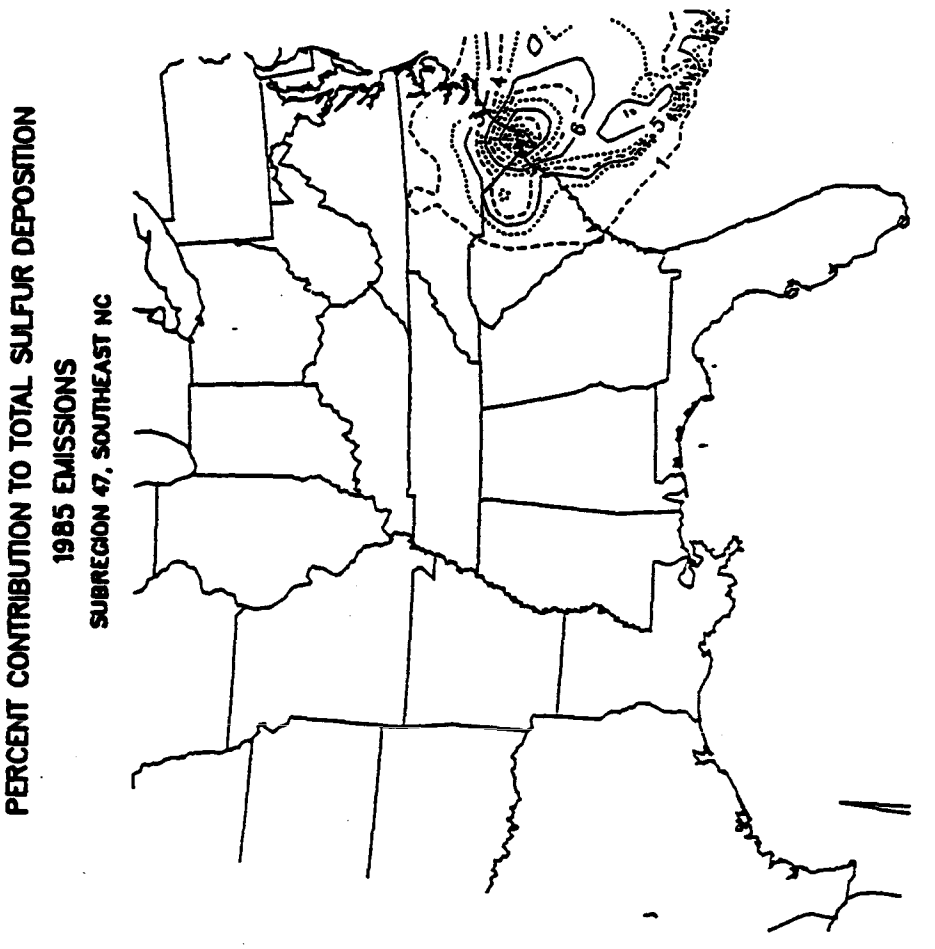


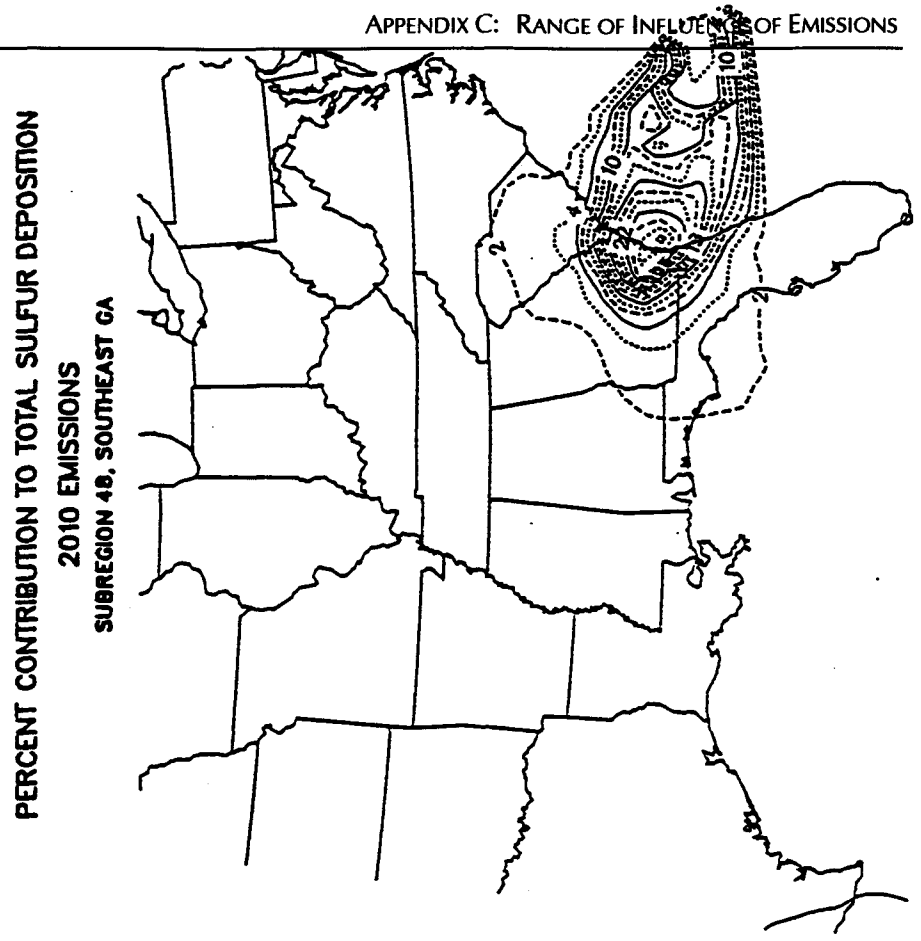
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 45, ADIRONDACKS

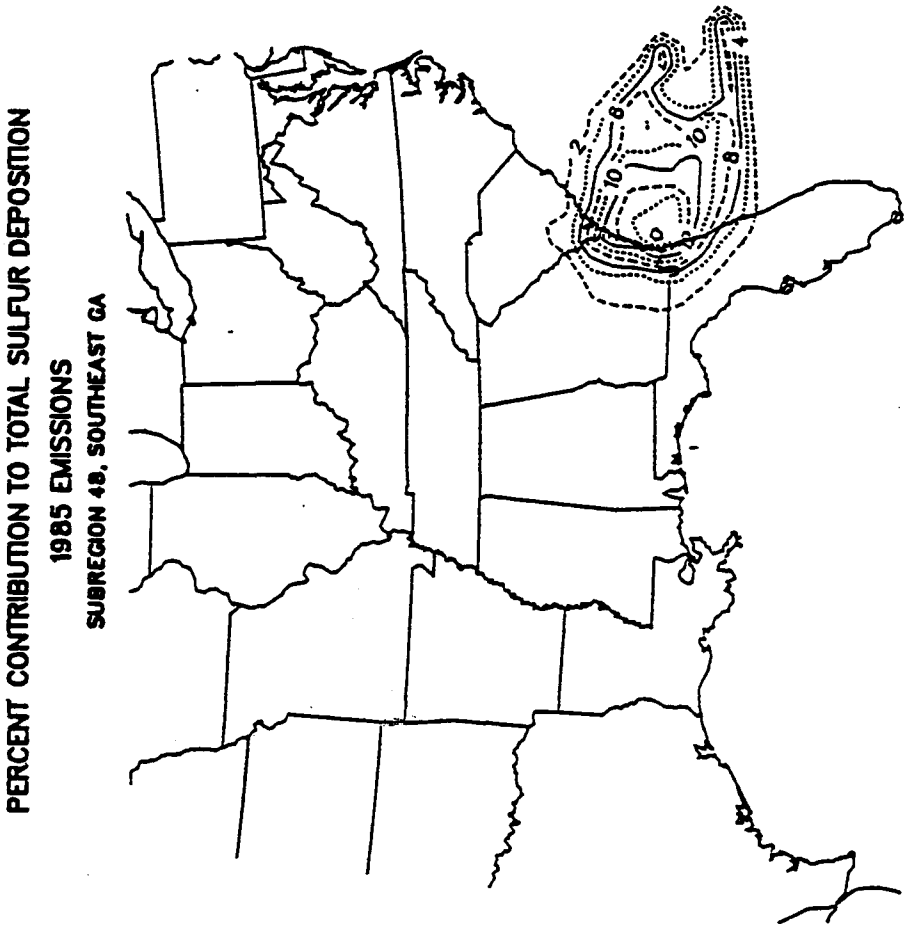


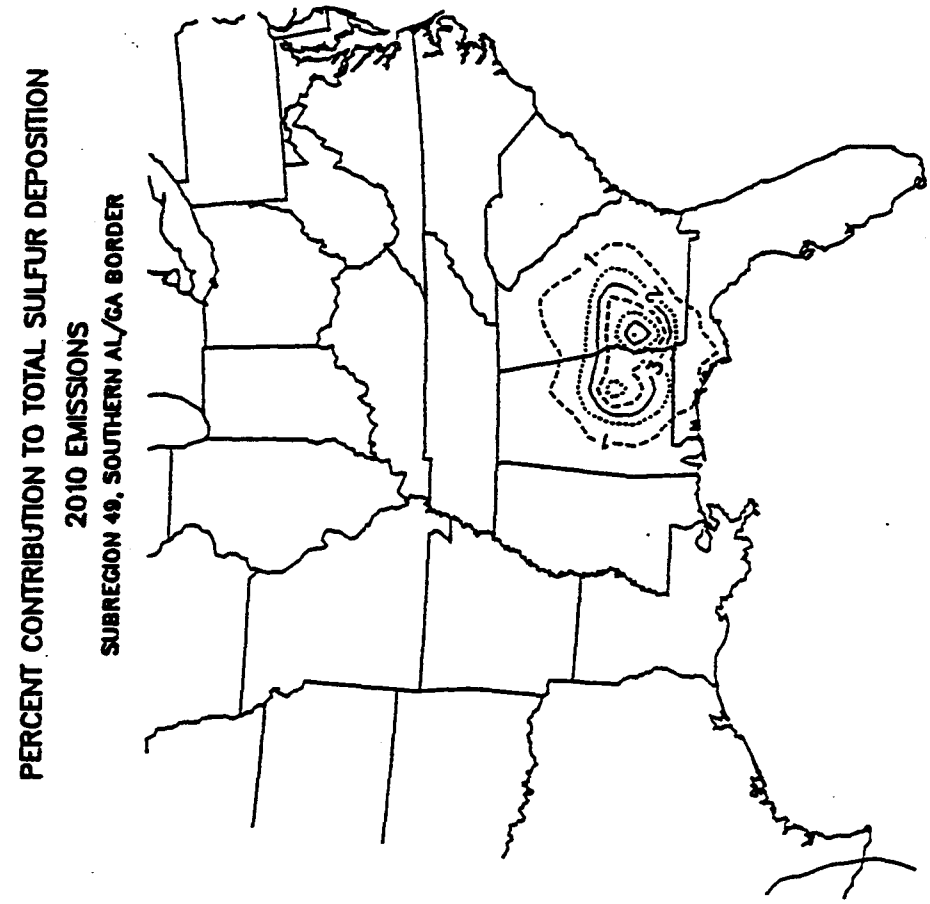
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 46, VT/NH
0.5
2.0
2.5
PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 46, VT/NH
1.0
2.0

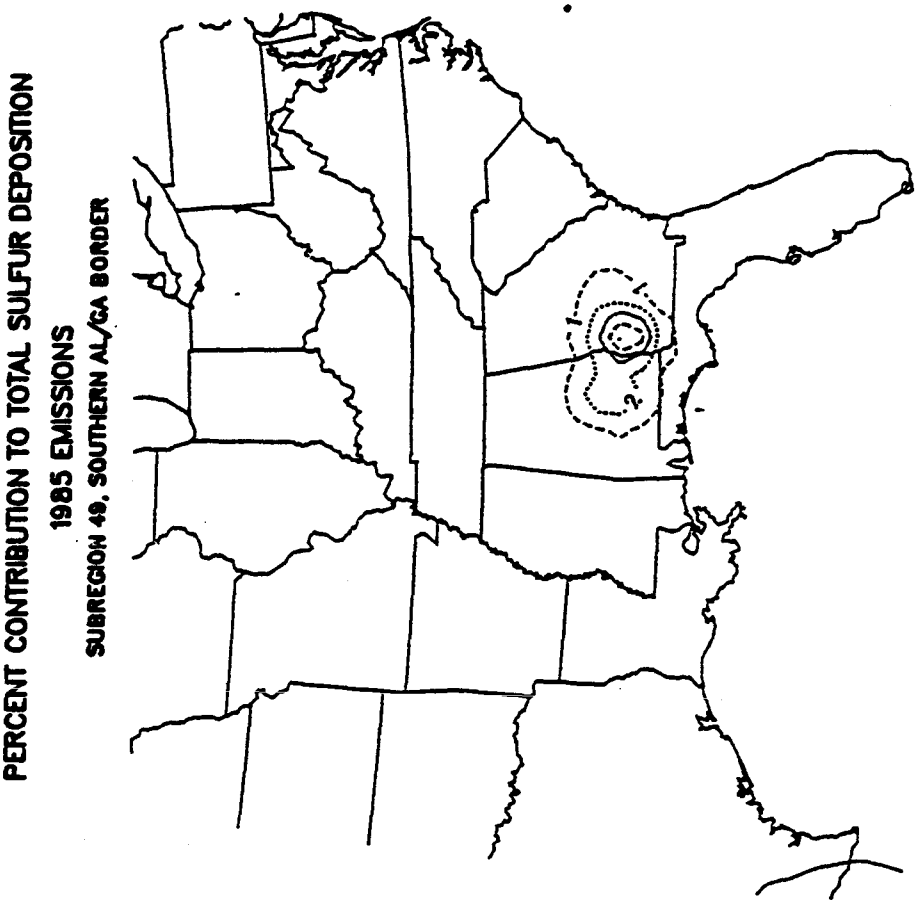

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 47, SOUTHEAST NC

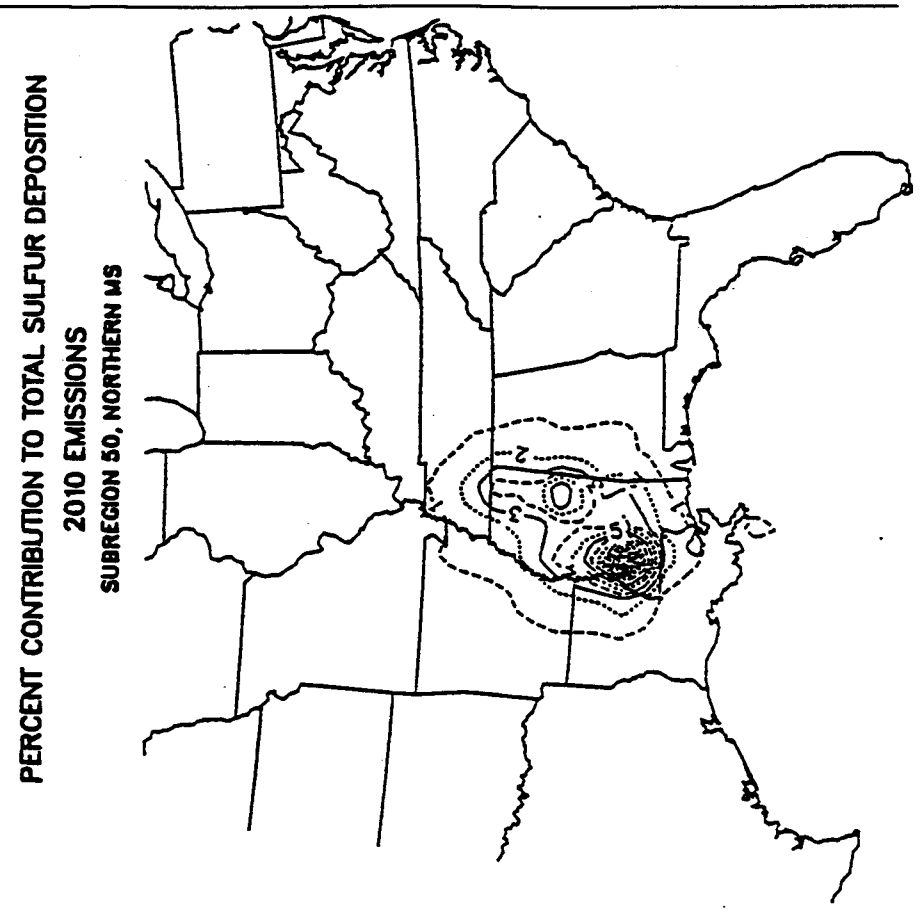

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 47, SOUTHEAST NC

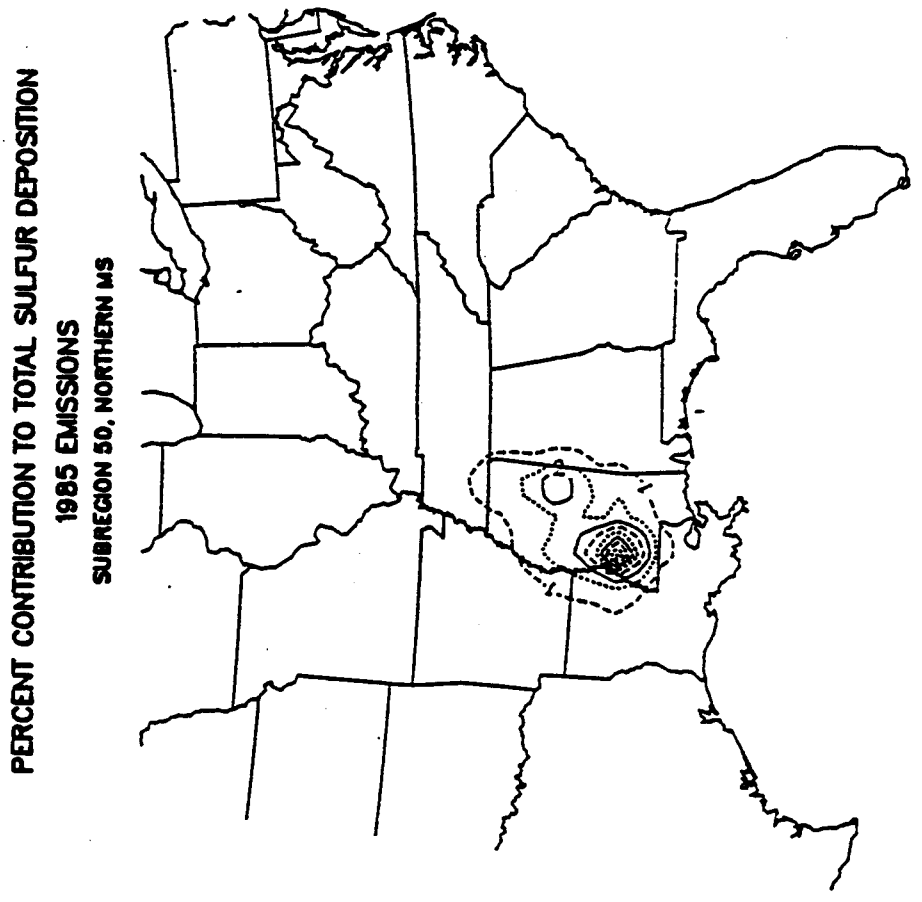

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 48, SOUTHEAST GA

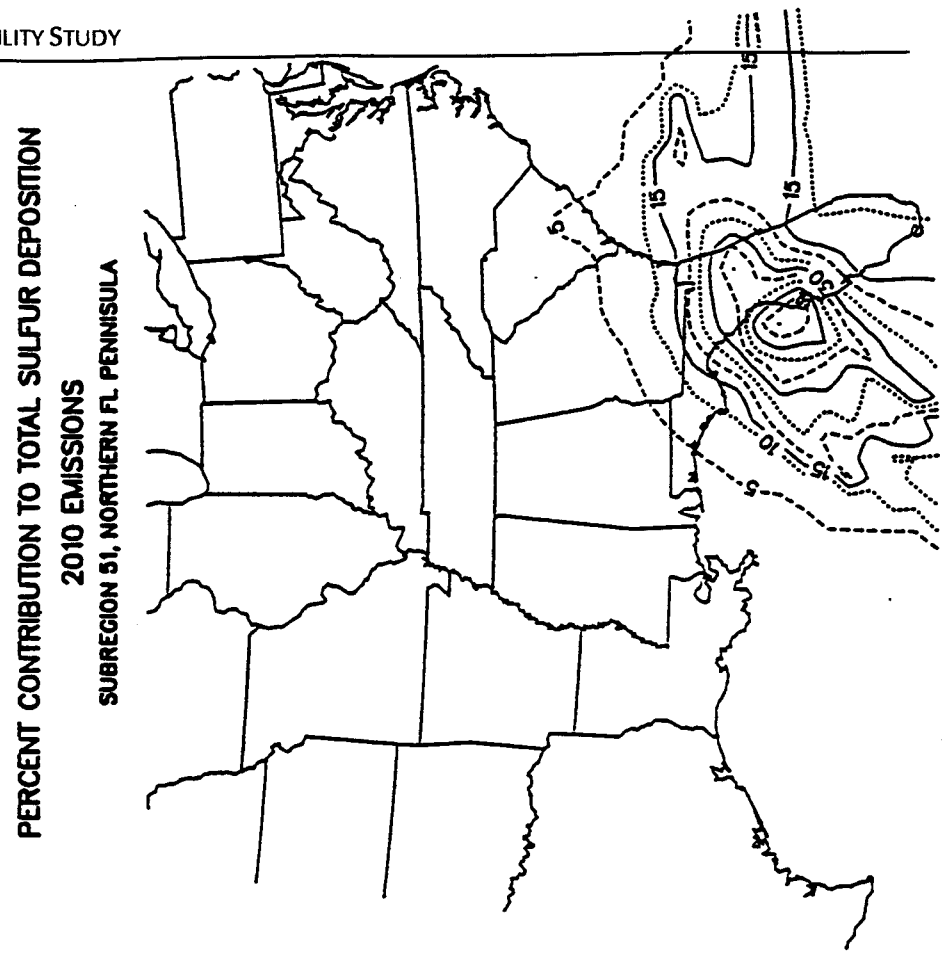

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 48, SOUTHEAST GA

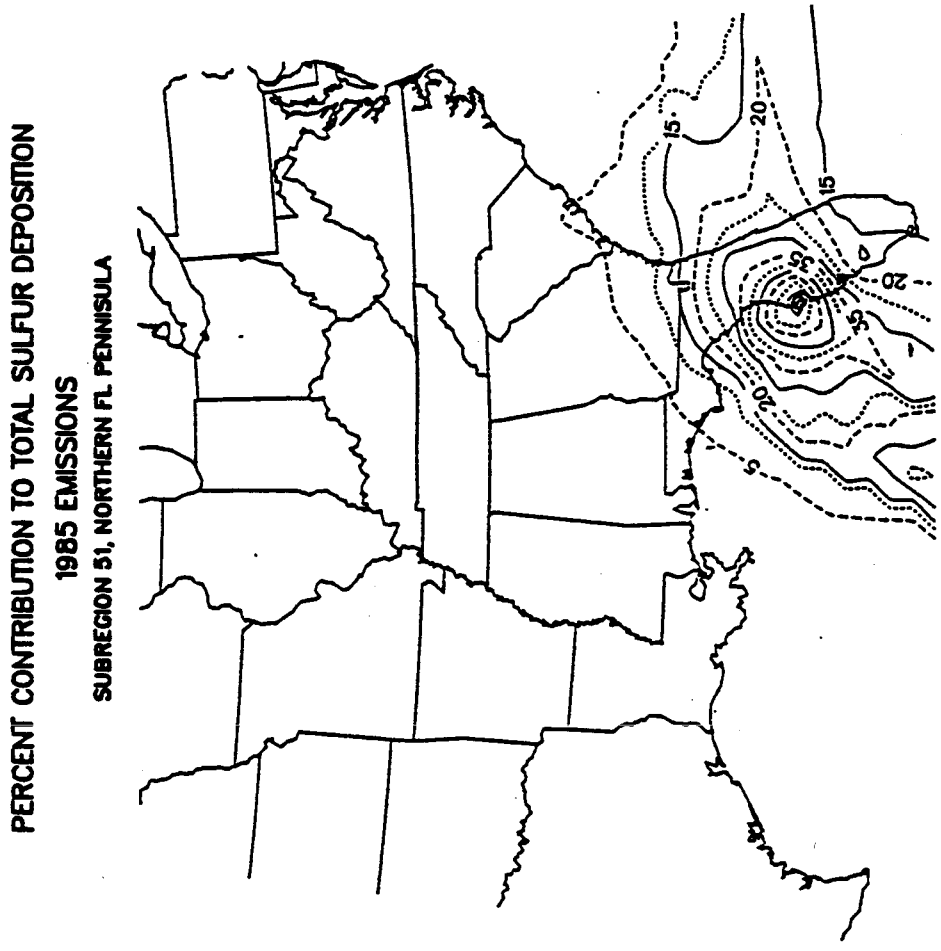

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 49, SOUTHERN AL/GA BORDER

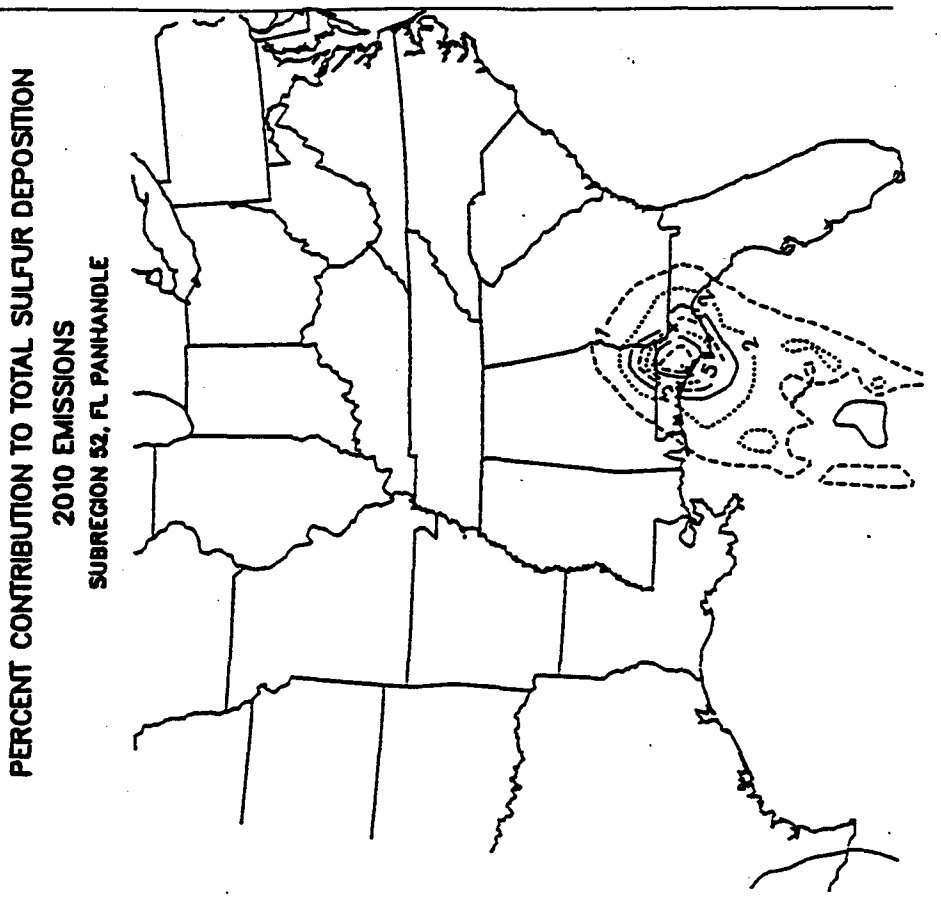

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 49, SOUTHERN AL/GA BORDER

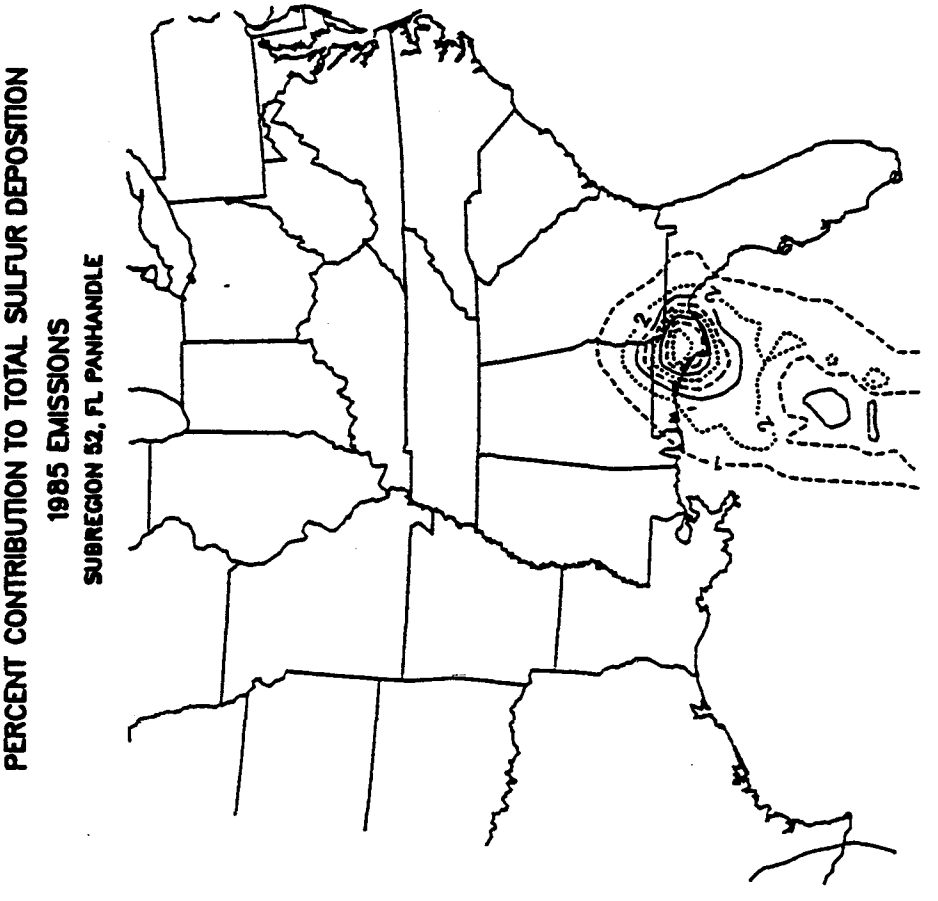

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 50, NORTHERN MS
2
3
5


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 50, NORTHERN MS

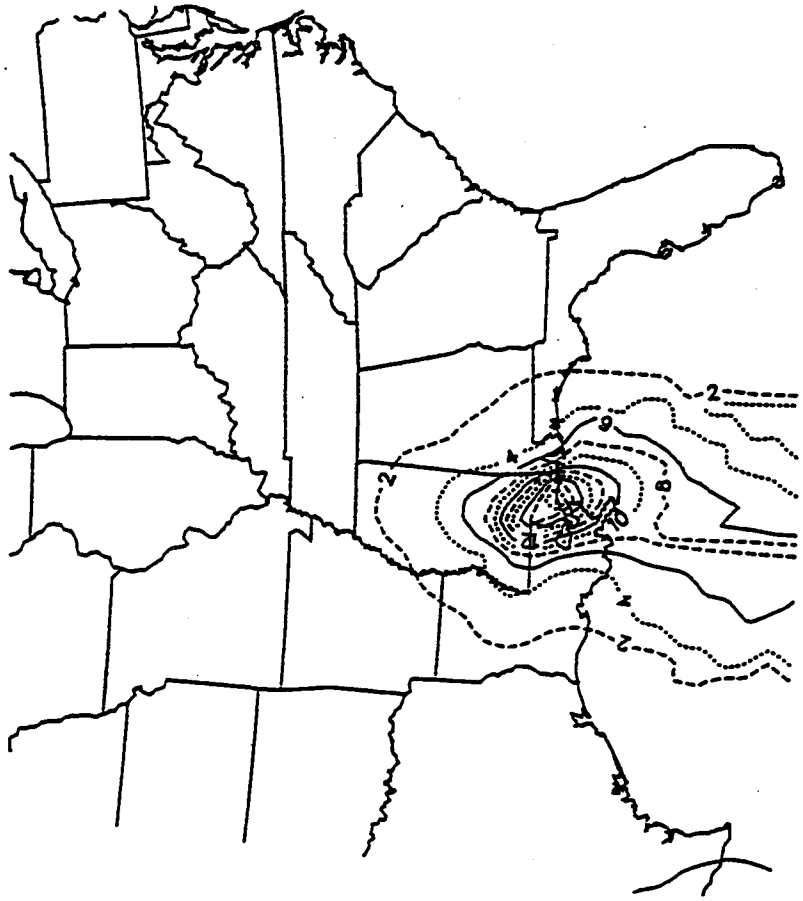

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 51, NORTHERN FL PENNISULA
5
10
15
20
30


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 51, NORTHERN FL PENNISULA
5
10
15
20
25
30
35


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 52, FL PANHANDLE


PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 52, FL PANHANDLE

PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
2010 EMISSIONS
SUBREGION 53, SOUTHERN MS



PERCENT CONTRIBUTION TO TOTAL SULFUR DEPOSITION
1985 EMISSIONS
SUBREGION 53, SOUTHERN MS