Appendix B
Effects of Transported Pollutants

B. 1 AQUATIC RESOURCES AT RISK

*Extent of Resources at Risk**

Scientists are concerned that acid deposition may be damaging substantial numbers of U. S. and Canadian lakes and streams. As part of its assessment of transported air pollutants, OTA contracted with The Institute of Ecology (TIE) to:

- describe mechanisms by which acid deposit ion may be affecting sensitive 1akes and streams;
- providc an inventory of Eastern U.S. lakes and streams considered to be sensitive to acid deposit ion;
- estimate the number of lakes and streams in these scnsitive regions that have been affected and/or altered by acidic deposition; and
- examine three scenarios for future sulfate deposition levels to the year 2000, and project effects on sensitive aquatic resources.

Because of' scientific uncertainties and data limit ations, none of these tasks can be addressed at this time with a high degree of accuracy. Each of' these topics is the subject of active research under the National Acid Precipitation Assessment Program (NAPAP). To illustrate, the estimates of the numbers of lakes and streams sensitive to acid deposition are based on eight separate water quality surveys conducted at different times using nonuniform procedures. NAPAP is currently planning to undertake a national survey-sampling several thousand water bodies over a much wider geographic area—to provide a more complete picture of the current magnitude of the problem.

Because of the large area of a typical watershed, most of the acid ultimately deposited in lakes and streams comes from water that runs off or percolates through the surrounding land mass, rather than from precipitation falling directly on water bodies. The amount of acidifying material that actually enters a given lake or stream is determined primarily by the soil and geologic conditions of the surrounding watershed. Whcn the two major chemical components of' acid rain-nitric acid and sulfuric acid—reach the ground, they may react with soils is a variety of ways. * * For example, soils can neutralize the acids, exchange nutrients and trace metals for components of the acids, and/or hold sulfuric acid.

Most soils contain amounts of counterbalancing (neutralizing) substances such as bicarbonate that may be available to ‘ ‘buffer” acid inputs. Such nutrients as calcium and magnesium, when present in soils, may be leached by acidic deposition and enter water bodies, while acidity remains in the soil. When soils are highly acidic, similar leaching of toxic metals such as aluminum can occur, which may cause damage to aquatic life in lakes and streams. In add it ion, the soils of some watersheds are able to retain sulfuric acid to varying degrees. For these areas, deposited sulfuric acid will not pass into lakes and streams until the ‘ ‘adsorption” capacity ‘‘ of the soils is exceeded.

The extent to which such reactions actually occur depends on a number of geologic and soil conditions. Where slopes are relatively steep, and soils are thin, less opportunity exists for acid precipitation to infiltrate soil

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* I his sec tion adapted from Ihe Institute of Ecology “Regional Assessment of Aquatic Resc 111 rc (,\ at Risk from Acidic Deposit ion, ( ) 1A (ontract on {-)( )n , 1'IH.!

‘ ● l;,)! current attempts to assess the effects of acid deposition on aquatic ecosystems, sulfuric ac Id is considered the principal substance of(oncern The importance of atmospheric inputs of nitric acid to aquatic systems is still uncertain because the n itric ac(I (can be used as a plant nutrient Although nitric acid deposition may influence spring acidification (depression of pH) due to snowmelt, it is unlikely to have ,111 appreciable (.11((t(on mid summer ac 11111 v

layers and react chemically with soil components. Further, the composition of soils—the availability of neutralizing material, exchangeable elements, or sulfuric acid adsorption capacity—also affects their overall ability to mitigate acid deposition inputs to water bodies. Watersheds in a number of regions are believed to provide aquatic resources with virtually complete protection from current levels of acid deposition. In other regions, however, watersheds have little capacity to neutralize acidic substances, and much of the acid in precipitation in these regions moves through the watershed into lakes and streams.

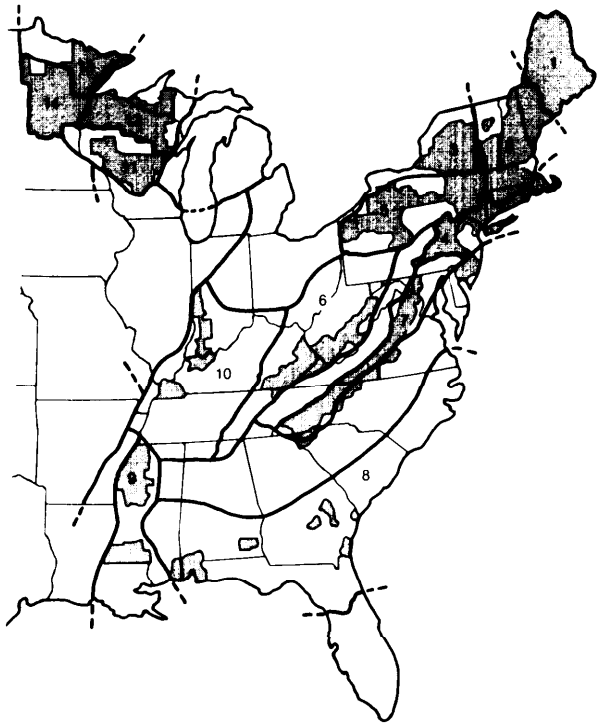
Under unaltered conditions, virtually all lakes and streams also have some acid-neutralizing capacities. Like soils, their waters contain such substances as bicarbonate, which neutralize the entering acids. Alkalinity levels, which are expressed in microequivalents per liter of water (μeq/1), measure the acid-neutralizing capacity of lakes and streams. Lakes and streams defined as very sensitive to acidic inputs have alkalinity levels of O to 40 μeq/1, while a lake with high capacity for acid neutralization can measure over 500 μeq/1. * If the surrounding watershed contains little neutralizing material, natural alkalinity levels in lakes and streams may be quite low, making these aquatic resources highly sensitive to even low levels of acidic inputs.

When acids enter a lake or stream, available neutralizing substances are consumed, and alkalinity levels are depressed. As water bodies become acidified, aquatic plant and animal populations may be altered. A lake or stream is considered to be acidified when no neutralizing capacity is left. Such bodies of water have been measured as having negative alkalinity levels as great as –100 μeq/1.

A multistep process was employed to develop an inventory of sensitive (but not necessarily altered) lakes and streams in the Eastern United States. TIE (adapting a procedure developed by Oak Ridge National Laboratory) first used data on soil, watershed, and bedrock characteristics in 27 Eastern States to generate a list of individual counties whose freshwater resources were likely to be sensitive to acidic deposition. The list of counties was then aggregated into 14 acid-sensitive regions (fig. B-l). Using U.S. Geological Survey maps, the contractor systematically sampled each region to estimate its total number of lakes greater than 15 acres in size, and total miles of first- and second-order streams,** The results show an estimated 17,000 lakes and 117,000 miles of first- and second-order streams in the 14 sensitive regions (table B-l).

Of this total number of lakes and streams in the sensitive regions, only a portion may be considered sensitive to acid inputs, Local variations in geology, soil conditions, and runoff patterns cause alkalinity levels of lakes and streams within a sensitive region to range from less than zero μeq/1 (acidified) to over 500 μeq/1 (acid resistant). Regional water quality surveys*** were used to estimate the percentage of the lakes and streams in the 14 regions that can be considered sensitive to acid

Figure B-1.—Areas Sensitive to Acid Rain (shaded grey)



Lake and stream sampling areas modified from Braun (1950) and Fenneman (1938). Region numbers correspond to those shown in table B-1.

"Reports by J. R. Kramer (3), H. Harvey, et al (4), and others have divided the spectrum of their sensitivity measure into a series of intervals referred tn as sensitivity classes or categories Each approach differed slightly from the others, leading the authors of the U S -Canada Aquatic Impacts Assessment Subgroup (5) to propose the following classification for lakes:

Class		Alkalinity (μeq/l)
I	Acidified	< 0
II	Extreme sensitivity	0-39
III	Moderate sensitivity	40.199
IV	Low sensitivity	200-499
V	Not sensitive	≥ 500

● *The smallest unbranched tributary of a stream is a first-order stream; the junction of two first-order streams produces a second-order stream segment,

* * "Eight surveys of lake and stream water quality were used to evaluate the regional sensitivity of aquatic ecosystems to acid deposition. Regional estimates are based on measurements from about 40 New England streams (6), 430 Adirondack lakes (7), 45 Pennsylvania streams (8), 40 streams in North Carolina and Virginia (9), 360 lakes in Wisconsin (10) and Minnesota (1 1), and 40 Wisconsin streams (12)

Table B-1 .—Total Estimated Lake and Stream Resources in the Acid-Sensitive Regions of the Eastern United States (see **fig. B-1)**

Region	Sensitive area (mi^2)	Total lakes		Total streams (mi)	
		Number	Acres	1st order	2d order
1. Eastern Maine	26,398	1,425	582,825	9,714	3,485
2. Western New England	29,666	1,543	763,785	15,308	4,569
3. Adirondacks	14,066	1,139	231,217	5,289	3,024
4. East Pennsylvania South New England	20,947	1,320	118,800	8,400	2,556
5. West New York/Pennsylvania	25,051	376	16,920	7,114	1,678
6. Appalachian Plateau	16,190	13	29,510	7,350	2,299
7. Blue Ridge/Great Smoky Mountains	20,964	126	14,868	10,901	3,396
8. Coastal Plain	9,264	241	8,917	1,547	713
9. Lower Mississippi	13,075	170	56,610	5,374	1,255
10. Indiana/Kentucky	8,603	9	603	2,805	989
11. Central Wisconsin	12,141	583	187,726	2,683	728
12. Wisconsin/Michigan Highlands	19,229	5,307	801,357	5,037	1,737
13. Northeast Minnesota	10,560	1,637	473,093	1,637	475
14. Central Minnesota	18,870	3,170	323,340	4,831	2.529
Totals	245.024	17.059	3.609.571	87,990	29,433

SOURCE: "Regional Assessment of Aquatic Resources at Risk From Acidic Deposition, " prepared for OTA by The Institute of Ecology, June 1982

deposition, using a 200-µeq/1 alkalinity level as the cutoff point between sensitive and nonsensitive lakes and streams. Results show an estimated 9,400 lakes and 60,000 miles of streams that are currently sensitive to further acid inputs (tables B-2 and B-3).

To estimate the portion of these sensitive lakes and streams that already have been altered by acidic deposition, TIE compared data on the distribution of alkalinity levels for two distinct geographic areas: 1) regions with little neutralizing capacity that currently receive high (resource-affecting) levels of acidic deposition; and 2) geologically similar areas of northwestern Ontario and northern Minnesota having little neutralizing capacity, but that receive negligible amounts of acid deposition. The difference between the two distributions provides an estimate of the proportion of lakes and streams that can be considered ' 'acid-altered, rather than simply sensitive. Only lakes with alkalinity levels less than 40 µeq/1 and streams with less than 100 µeq/l—already acidified or extremely sensitive to further alteration—are considered in these calculations. Calculations using this approach show an estimated 3,000 lakes and 23,000 miles of streams with alkalinity levels that can be described as already acid-altered. This corresponds to 18 percent of the lakes and 20 percent of the streams located within the 14 sensitive areas (see tables B-4 and B-5).

Finally, TIE employed a simple model to estimate the effects on aquatic resources of three possible future acid deposition scenarios. As an underlying assumption, the model uses an empirical measure to project changes in lake and stream alkalinities given a change in sulfate deposition. This measure—the ' 'alkalinity impact parameter' —is based on both limited observations of alkalinity changes through time in areas where sulfate deposition has been increased or reduced, and on current theory about the processes involved. * Although not yet fully tested, the model suggests that lake and stream alkalinities are likely to respond to future changes in sulfate deposition. The model cannot address further changes in lake and stream water quality that might occur if deposition remains constant over the next several decades.

For scenario I, a 10-percent increase in sulfate deposition by 2000, the model projects that 5 to 15 percent (depending on the region) of the most sensitive lakes and streams worsen in condition—becoming either ' 'acidified' or ' 'extremely sensitive' to acid inputs.

*An empirical "alkalinity impact parameter" (AIP) can be defined as the ratio of observed changes in lake and stream alkalinity levels to changes in sulfate loadings. When sulfate retention by the watershed approaches zero, nitrate uptake by plants is high, and further losses of nutrient cation \—e g , calcium and magnesium—are low or negligible, acidity (H_2SO_4) directl, affects alkalinity (HCO_3), and the expected .41P is '2 For the case in which some neutralization of acid input occurs in the watershed, the AIP would be less than 2: during the very *early stages* of acidic deposition. it should approach zero Where soils have high sulfate adsorption capacity, the AIP would also approach zero during the early stages of an acidification process, later, if acid deposition to the watershed is decreased, some of the sulfate previously retained can be washed from the soil, and AIP values could exceed 2 Calculations using an AIP of greater than 2 were not considered, since many of the watersheds In the regions mapped as sensitive for this study have low sulfate adsorption capacities

The importance of atmospheric deposition of calcium and magnesium as potential neutralizing agents has been considered For the areas examined, calcium and magnesium deposition appear to be only one-tenth the magnitude of sulfate deposition. therefore, its role has been considered negligible for the present calculations.

Table B-2.-Estimated Lake Resources at Risk in the Acid-Sensitive Regions of the Eastern United States

Region	Sensitive area (mi^2)	Total number lakes	Percentage of lakes <200 µeq/l	Calculated number of lakes at risk
1. Eastern Maine	26,398	1,425	(80)[a]	1,140
2. Western New England	29,666	1,543	(80)[a]	1,234
3. Adirondacks	14,066	1,139		911
4. East Pennsylvania/ South New England	20,947	1,320	(80)[a]	1,056
5. West New York/Pennsylvania	25,051	376	(80[a]	301
6. Appalachian Plateau	16,190	13	—	—
7. Blue Ridge/Great Smoky Mountains.	20,964	126	—	
8. Coastal Plain	9,264	241	—	
9. Lower Mississippi	13,075	170	—	—
10. Indiana/Kentucky	8,603	9	—	.
11. Central Wisconsin	12,141	583	(42)[c]	245
12. Wisconsin/Michigan Highlands	19,229	5,307	42	2,228
13. Northeast Minnesota.	10,560	1,637	48	786
14. Central Minnesota	18,870	3,170	(48)[d]	1,522
Totals	245,024	17,059		9,423

[a]In the absence of other data, alkalinities from the Adirondacks have been '[Sea]l.

[b]No estimate is being made for regions with fewer than 250 lakes.
[c]In the absence of other data, alkalinities from north Wisconsin have been 'Seal

'In the absence of other data, alkalinities from north Minnesota have been used.

SOURCE' '(Regional Assessment of Aquatic Resources at Risk From Acidic Deposit ion," prepared for OTA by The Institute of Ecology, June 1982

Table B-3.—Estimated First- and Second-Order Stream Resources at Risk in the Acid-Sensitive Regions of the Eastern United States

Region	Sensitive area (mi^2)	Total streams (mi) 1st order	Total streams (mi) 2d order	Percentage of stream <200 µeq/l	Calculated total miles of: 1° streams at risk	Calculated total miles of: 2° streams at risk
1. Eastern Maine	26,398	9,714	3,485	81	7,868	2,823
2. Western New England	29,666	15,308	4,569	56	8,573	2,559
3. Adirondacks	14,066	5,289	3,024	(56)[a]	2,962	1,693
4. East Pennsylvania/South New England	20,947	8,400	2,556		3,192	971
5. West New York/Pennsylvania	25,051	7,114	1,678	61	4,340	1,024
6. Appalachian Plateau	16,190	7,350	2,299	(61)[b]	4,484	1,402
7. Blue Ridge/Great Smoky Mountains.	20,964	10,901	3,396		6,977	2,173
8. Coastal Plain	9,264	1,547	713	(43)[c]	665	307
9. Lower Mississippi	13,075	5,374	1,255	(43)'	2,311	540
10. Indiana/Kentucky	8,603	2,805	989	(43)[c]	1,206	425
11. Central Wisconsin	12,141	2,683	728		1,154	313
12. Wisconsin/Michigan Highlands	19,229	5,037	1,737	13	655	226
13. Northeast Minnesota.	10,560	1,637	475	(13)[d]	213	62
14. Central Minnesota	18,870	4,831	2,529	(13)[d]	628	329
Totals.	245,024	87,990	29,433		45,228	14,847

[a]In the absence of other data, alkalinities from west New England and west New York/Pennsylvania have been used.

[b]In the absence of other data, alkalinities from west New York/Pennsylvania have been used.
[c]In the absence of other data, alkalinities from central Wisconsin have been used.

'In the absence of other data, alkalinities from northern Wisconsin have been used,

SOURCE' "Regional Assessment of Aquatic Resources at Risk From Acidic Deposition," prepared for OTA by The Institute of Ecology, June 1982.

Table B-4.—Estimates of Extremely Sensitive or Acidified Lake Resources[a] in the Eastern United States

Region	Total number of lakes	1980 number of lakes with alkalinities <40 µeq/l	Historic number of lakes with alkalinities <40 µeq/l	1980 number of acid-altered lakes <40 µeq/l
1. Eastern Maine	1,425	456	43	413
2. Western New England	1,543	494	46	448
3. Adirondacks	1,139	456	34	422
4. East Pennsylvania/ South New England	1,320	423	40	383
5. West New York/Pennsylvania	376	150	11	139
6. Appalachian Plateau	13	—		—
7. Blue Ridge/Great Smoky Mountains	126			
8. Coastal Plain	241			
9. Lower Mississippi	170	—	—	—
10. Indiana/Kentucky	9	—	—	—
11. Central Wisconsin	583	134	17	117
12. Wisconsin/Michigan Highlands	5,307	1,220	159	1,061
13. Northeast Minnesota	1,637	49	49	0
14. Central Minnesota	3,170	95	95	0
Totals	17,059	3,477	494	2,983

Total number of lakes altered, Class I and II 2,983.
Percentage of lakes altered 18%.
[a]**Lakes with alkalinity less than 40 µeq/l, based on using 1980 calculated alkalinity depression and "historic" area alkalinity distributions as a control**

SOURCE"Reglonal Assessment of Aquatic Resources at Risk From Acidic Deposition," prepared for OTA by The Institute of Ecology, June 1982

Table B-5.—Estimates of Extremely Sensitive or Acidified Stream Resources[a] in the Eastern United States

Region	Total stream miles	1980 miles with alkalinities <100 µeq/l[b]	Historic stream miles with alkalinities <100 µeq/l	Acid-altered stream miles <100 µeq/l
1. Eastern Maine	13,199	3,746	816	2,930
2. Western New England	19,877	5,641	1,228	4,413
3. Adirondacks	8,313	3,060	514	2,546
4. East Pennsylvania/South New England	10,956	3,109	677	2,432
5.West New York/Pennsylvania	8,792	3,237	543	2,694
6. Appalachian Plateau	9,649	2,738	596	2,142
7.Blue Ridge/Great Smoky Mountains	14,297	4,058	884	3,174
8. Coastal Plain	2,260	482	140	342
9. Lower Mississippi	6,629	1,412	410	1,002
10. Indiana/Kentucky	3,794	809	234	575
11. Central Wisconsin	3,411	726	211	515
12. Wisconsin/Michigan Highlands	6,774	418	418	0
13. Northeast Minnesota	2,112	130	131	0
14. Central Minnesota	7,360	455	455	0
Totals	117,423	30,021	7,257	22,765

aStreams with alkalinity less than 100 µeq/l, based on **1980 calculated alkalinity depression and "historic" area alkalinity distributions as a control.**
bA higher alkalinity level was used to denote extreme sensitivity for streams than for lakes

SOURCE "Regional Assessment of Aquatic Resources at Risk From Acidic Deposition," prepared for OTA by The Insttiute of Ecology, June 1982

Under scenario II, which provides for a 20-percent decrease in sulfate deposition by 2000, 10 to 25 percent of the most sensitive lakes and streams are estimated to experience some recovery —i. e., ‘ ‘acidified’ aquatic resources become ‘ ‘extremely sensitive’ or ‘ ‘extremely sensitive’ resources become ‘ ‘moderately sensitive. Scenario III, which involved a 35-percent decrease in sulfate deposition by the year 2000, is estimated to result in some recovery for 14 to 40 percent of the most sensitive aquatic resources. *

Figures B-2 and B-3 summarize the projected effects of scenarios I, II, and III on lakes and streams in a number of the sensitive areas. Each bar graph illustrates scenarios 1, II, and III in that order. The two figures show the sum of the calculated shifts to or from the most sensitive resource categories, expressed as a percent of the total lake or stream resource in each area. The short, solid portion of each bar represents a highly probable response; the shaded portion of each bar represents the upper bound of the probable response.

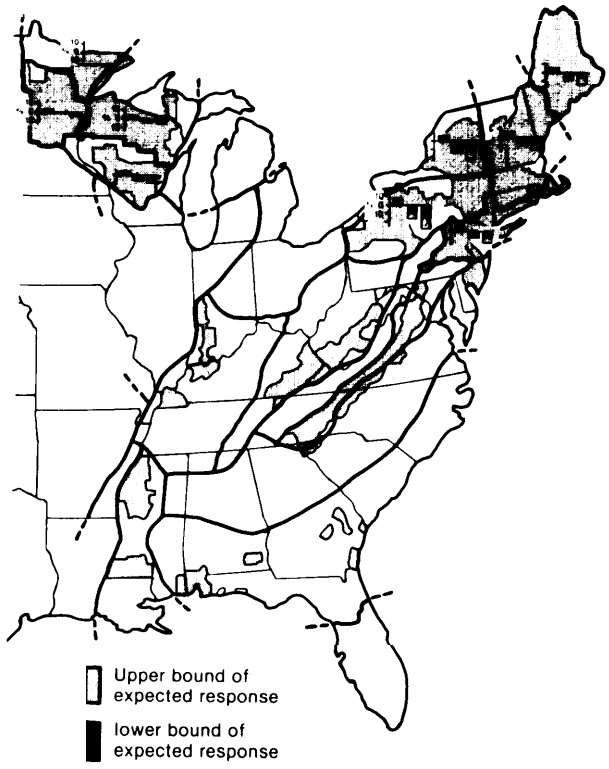
Scenario III (a 35-percent reduction in sulfate deposition by 2000) appears likely to result in relatively significant responses for the total resource. Recovery for lakes is projected to range from a few to about 30 percent in each area, and up to 20 percent for streams, with the greatest recovery in areas of highest current deposition.

While the model indicates some important prospects for recovery, it cannot address certain long-term consequences of acidification. Soils that may have been depleted of such nutrients as calcium and magnesium by acid deposition might take a great deal longer to recover normal nutrient levels than water bodies take to regain equilibrium alkalinity levels. If the soil’s ability to mitigate acid deposition recovers slowly, “acid shock ‘ ‘ episodes to water bodies from such events as spring snowmelt may persist for some time. The magnitude of such consequences is unpredictable at this time.

Lastly, some discussion of the implications of these results for biological responses in aquatic systems is required. Scientists are gradually developing an understanding of how fish and other aquatic life are affected by acid-induced alterations of their environments. Thus, predictive statements about changes in water quality over some period of abatement represent the first step in making predictive statements about the potential recovery of aquatic life.

“ Because the TIE model is most applicable to those lakes and streams in the acid-altered (Class 1 < 0 μeq/l) and extremely sensitive (Class 11 0 to 40 μeq/l) categories, TIE used transfers into and out of each of these categories as the measure of change fur aquatic resources in response to altered deposition To correct for differences in alkalinity distributions between streams and lakes, a defined portion of the streams in Class 111 (40 to 100 μeq/l) was included in the TIF, calculations

Figure B 2.—Lake Model Projections



Where there is no black band, the lower bound is zero)

Bar-graphs show the percent increase (or decrease) by the year 2000 in lakes classed as “acidified” or “extreme” for the three deposition scenarios I (a 10-percent increase in deposition), II (a 20-percent decrease), and III (a 35-percent decrease), represented by the bars, in that order from left to right.

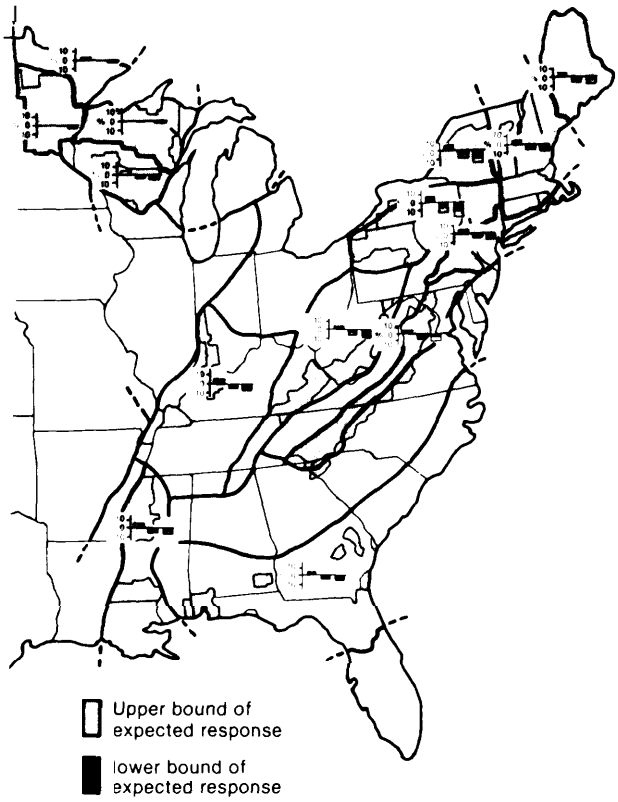
SOURCE: “Regional Assessment of Aquatic Resources at Risk From Acidic Deposition,” prepared for OTA by The Institute of Ecology, June 1982.

Effects of Acid Deposition on Aquatic Life

Losses of fish populations attributed to the effects of acid deposition have received a great deal of public attention; however, the available evidence indicates that acidic waters also affect many other forms of aquatic life, from single-celled algae to large aquatic plants to amphibians such as frogs and salamanders. Adverse effects on aquatic plants and animals can affect the availability of food to other animals such as fish, aquatic birds, and mammals.

Fish reproduction requires water pH levels of above 4.5, according to numerous laboratory studies and field surveys (13). The International Joint Commission has recommended a water quality standard of greater than

Figure B 3.—Stream Model Projections



(Where there is no black band, the lower bound is zero)

Bar-graphs show the percent increase (or decrease) by the year 2000 in lakes classed as "acidified" or "extreme" for the three deposition scenarios I (a 10-percent increase in deposition), II (a 20-percent decrease), and III (a 35-percent decrease), represented by the bars, in that order from left to right.

SOURCE "Regional Assessment of Aquatic Resources at Risk From Acidic Deposition, " prepared for OTA**by The Institute of Ecology, June 1982.**

pH 6.5 for successful fish reproduction. Death of adult fish does not generally occur until the pH is less than 5.0. Rapid decreases in stream and lake pH due to spring snowmelt and release of acid accumulated over the winter can be detrimental if they coincide with sensitive periods of the fish reproductive cycle. Several reports have documented sudden fish kills in both rivers and lakes associated with springtime pH depressions (14).

Survival of fish in water of low pH is influenced by temperature, presence of metals such as aluminum, hardness of the water, and type of acid input. Aluminum increases the sensitivity of fish to low pH levels (15). Increases in the concentration of aluminum are correlated with decreasing pH. Fish mortalities have been documented as a result of increased aluminum concentrations, increased acidity, and the combination of these two factors. The hardness of the water (mineral content) increases the ability of fish to withstand low pH; fish communities disappear from soft waters at higher pH than they do from hard waters (16).

A recent inventory (1980)(17) of the New York State Adirondacks (one of the largest sensitive lake districts in the Eastern United States receiving significant amounts of acid deposition) indicates that the brook trout fishery has been most severely affected by acidification. At least 180 former brook trout ponds in the Adirondacks will no longer support populations. A survey of 214 Adirondacks lakes in 1975 revealed that 52 percent had surface pH levels below 5.0, and that 90 percent of these were entirely devoid of fish life. Some of these lakes had been surveyed between 1929 and 1937, when only 4 percent (or 10 lakes) were below pH 5.0 and devoid of fish; over the intervening forty years entire fish communities of brook trout, lake trout, white sucker, prawn bullhead, and several cyprinid species were eliminated (1 8).

Similar losses of fish species have been observed in acidic lakes in the La Cloche mountain range of Ontario, Canada (19). These field studies performed over time show that species vary in their susceptibility to declining pH, and that the mechanisms by which individual species are eliminated are complex. In Nova Scotia there are nine rivers with pH less than 4.7 which previously had salmon that can no longer sustain trout or salmon reproduction (20). Losses to brook trout populations in the Great Smoky Mountain National Park have also been associated with the acidity of streams and aluminum concentrations (21).

In the field, mass mortalities of fish have been observed during the spring due to the ''acid shock' from high concentrations of pollutants in snowmelt. Elevated concentrations of aluminum mobilized from the soils by strong acids present in snowmelt water are thought to be a contributing factor to such large-scale fish mortality (22). Increases in juvenile salmon mortality in Nova Scotia hatcheries have also been associated with snowmelt-induced pH depressions (23).

Field surveys and laboratory experiments have shown amphibian populations, such as frogs and salamanders, to be extremely sensitive to changes in pH. Many species breed in temporary pools that may be formed from low-pH meltwater in spring. Because of the great vulnerability of their habitat to pH depressions, damage to amphibian populations may be one of the earliest consequences of acidification of freshwaters. Experiments have shown correlations between pH and both mortality and embryo deformity in frog and salamander populations (24).

Numerous invertebrate animals are known to be affected by the acidification of water, although individual

species may vary greatly in sensitivity. Of these, shell-bearing organisms and molting crustaceans appear to be the most sensitive to low pH (25). No molluscs are known to inhabit waters of pH lower than 6.0, while most crustaceans (e. g., crayfish) are absent from waters of pH below 4.6 (26). Aquatic insects exhibit a wide range of sensitivities to pH (27).

Single-celled algae are a basic constituent of the aquatic food chain. Studies have shown that as pH decreases, significant changes occur in the species and diversity of algae that predominate (28). As lakes or streams acidify, acid-tolerant algae proliferate (29). This group of algae is not readily edible by zooplankton, the animals that link algae and smaller fish in the food chain. However, a recent study suggests that algal species have some capability to adapt to acidic environments over the long term. This may explain the observation that a group of relatively recently acidified lakes in Norway have less diverse algae than natural historically acidic lakes (30).

Changes in algae community structure induced by acidification may also alter zooplankton community structure. Acidification of lakes is accompanied by changes in abundance, diversity, and seasonality of zooplankton which may reflect changes in their food base (algae), predators (fish), and/or complex changes in water chemistry, Since both population density and average size of the animals are reduced, food availability to fish and other animals may be reduced (31).

Limited findings from New York State suggest that acid-tolerant algae may cover submerged aquatic plant communities in acidic lakes, thereby preventing them from receiving the sunlight necessary for growth (32). Studies of Swedish lakes and preliminary information from New York, Nova Scotia, and Ontario have shown that acidification tends to cause decline of aquatic plants and replacement by growths of sphagnum mosses on lake and river bottoms (33). Sphagnum moss creates a unique habitat which is considered unsuitable for some species of bottom-dwelling invertebrates or for use as fish spawning and nursery grounds (34). Dense sphagnum beds may also reduce the appeal of freshwater lakes and rivers for recreational activities.

A number of studies have also found that acidic waters are more favorable to fungi than to normal bacterial populations. In many Scandinavian lakes studied to date, an increase in bottom accumulation of organic matter has been observed. This has been attributed to a shift in dominance from bacteria to fungi, which are less effective at decomposing organic material and which delay the recycling of nutrients (35).

Table B-6 and figure B-4 summarize the effects of decreasing pH on aquatic organisms. Table B-6 describes biological processes affected in different organisms as the pH of water decreases. Figure B-4 displays the percent of each of 7 major categories (taxonomic groups) remaining as pH decreases. For example, at pH 7, 100 percent of normal mollusc species are present. As pH decreases, the number of species remaining decreases rapidly. At a pH of 5.5, all mollusc species have disappeared.

Table B-6.-Effects of Decreasing pH on Aquatic Organisms

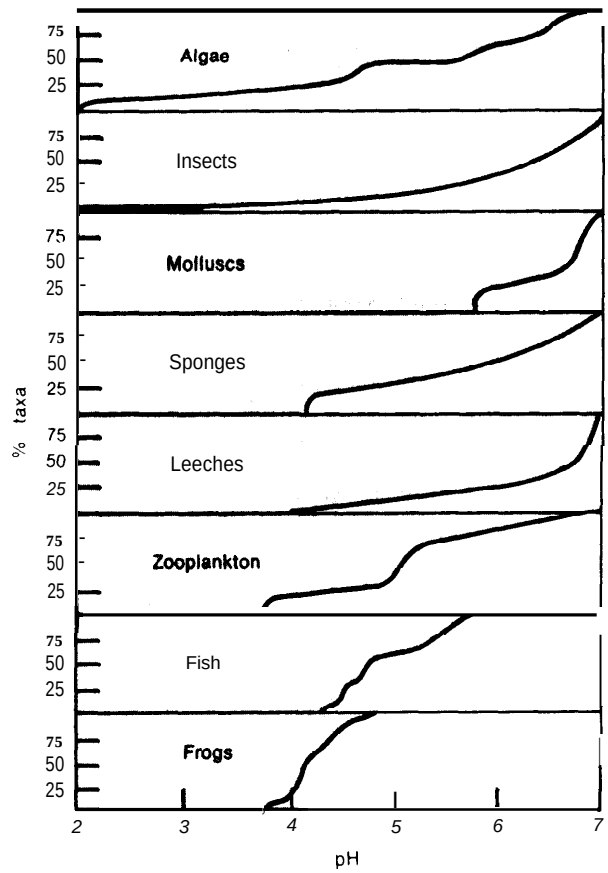
pH	Effect
8.0-6.0	In the long run, decreases of less *than one-ha/f of a pH unit* in the range of 8.0 to 6.0 are likely to alter the biotic composition of lakes and streams to some degree. However, the significance of these slight changes is not great. Decreases of *one-ha/f to one pH unit* (a threefold to tenfold increase in acidity) may detectably alter community composition. Productivity of competing organisms will vary. Some species will be eliminated.
6.0-5.5	Decreasing pH from 6.0 to 5.5 will reduce the number of species in lakes and streams. Among remaining species, significant alterations in the ability to withstand stress may occur. Reproduction of some salamander species is impaired,
5.5-5.0	Below pH 5.5, numbers and diversity of species will be reduced. Reproduction is impaired and many species will be eliminated. Crustacean zooplankton, phytoplankton, molluscs, amphipods, most mayfly species, and many stone fly species will begin to be eliminated. In contrast, several invertebrate species tolerant to low pH will become abundant. Overall, invertebrate biomass will be greatly reduced. Certain higher aquatic plants will be eliminated.
5.0-4.5	Below pH 5.0, decomposition of organic detritus will be impaired severely. Most fish species will be eliminated.
4.5 and below	In addition to exacerbation of the above changes, many forms of algae will not survive at a pH of less than 4.5.

SOURCE: International Joint Commission, Great Lakes Advisory Board (1979), after Hendrey, 1979.

B. 1 References

1. Braun, E. 1.., *Deciduous Forests of Eastern North America* (Philadelphia, Pa.: The Blakiston Co,, 1950).
2. Fenneman, N. M., *Physiography of the Eastern United States* (New York: McGraw-Hill Book Co., 1938).
3. Kramer, J. R., "Geochemical and Lithological Factors in Acid Precipitation, USDA Forest Service General Technical Report NE-23, 1976.
4. Harvey, H. H., Pierce, R. C., Dillon, P. J., Kramer, J. P., and Whelpdale, D. M., "Acidification in the Canadian Aquatic Environment: Scientific Criterion for Assessing I+; ffects of Acidic Deposition on Aquatic Ecosystems

Figure B-4.— Relative Number of Taxa of the Major Taxonomic Groups as a Function of Acidity



SOURCE *Impact* Assessment, Work Group 1, United States - Canada Memorandum of Intent on Transboundary Air Pollution. Final Report, January 1983

(Ottawa, Ontario, Canada: National Research Council Canada, NRCC No. 18475, 1981).

5. U.S.-Canada Memorandum of Intent on Transboundary Air Pollution, ' 'Impact Assessment, Work Group I, Phase II Interim Working Paper (Washington, D. C., and Ottawa, Ontario, Canada, 1981).
6. Haines, T. A., " Effects of Acid Rain on Atlantic Salmon Rivers and Restoration Efforts in the United States, *Proceedings of the Conference on Acid Rain and the Atlantic Salmon, Portland Maine, November 22-23, 1980,* International Atlantic Salmon Foundation Special Publication Series No. 10, March 1981 (New York: IASF, 1981).
7. Pfeiffer, M. H., and Festa, P. J., "Acidity Status of Lakes in the Adirondack Region of New York in Relation to Fish Resources. Progress Report' (Albany, N. Y.: New York State Department of Environmental Conservation, 1980).
8. Arnold, D. E., ' 'vulnerability of Lakes and Streams in the Middle Atlantic States to Acidification, Interim Progress Report (University Park, Pa. : Cooperative Fisheries Research Unit, Pennsylvania State University, 1981).
9. Hendrey, G. R., Galloway, J. N., Norton, S. A., Schofield, C. L., Shaffer, P. W., and Burns, D. A., ' 'Geological and Hydrochemical Sensitivity of the Eastern United States to Acid Precipitation" (Corvallis, Oreg.: U.S. EPA Environmental Research Lab, EPA-600/3-80-024, 1980).
10. Eilers, J. (with 12 other authors), "Acid Precipitation Investigation for Northern W isconsin, Progress Report (Duluth, Minn.: Wisconsin DNR, Rhinelander; and U.S. EPA-ERL, 1979).
11 Glass, G. E., and Loucks, O. L. (eds.), ' 'Impacts of Airborne Pollutants on Wilderness Areas Along the Minnesota-Ontario Border, EPA-600/3-80-044 (Duluth, Minn.: U.S. EPA Environmental Research Lab, 1980).
12 Andrews, L. M., and Threinen, C. W., "Surface Water Resources of Oneida Count?. ' (Madison, Wis.: Wisconin Conservation Department Report, 1966); and Klick, T. A., and Threinen, C. W., "Surface Water Resources of Jackson County, Lake and Stream Classification Project' (Madison, Wis.: Department of Natural Resources, 1968).
13. Beamish, R. J., "Acidification of Lakes in Canada by Acid Precipitation and the Resulting Effects on Fishes, *Water, Air, Soil Pollut. 6:50* 1-514, 1976; and EIFAC (European Inland Fisheries Advisory Commission), "Water Quality Criteria for Freshwater Fish, Report on Extreme pH Values and Inland Fisheries, *Water Res. 3* :593-611, *1969.*
14 Harvey, H. H., "The Acid Deposition Problem and Emerging Research Needs in the Toxicology of Fishes, Proc. 5th Annual Aquatic Toxicity Workshop, Hamilton, Ontario, Nov. 7-9, 1978, *Fish. Mar. Serv. Tech. Rep.* 862:1 *15-128, 1979.*
15 Davis, J. M., External Review Draft, Research Triangle Park, N. C., U.S. Environmental Criteria and Assessment Office, 1980; and Dickson, W., ' 'Some Effects of the Acidification of Swedish Lakes, *Verh. Int. Verein. Limnol.* 20:851 -856, 1978.
16 Leivestad, H., Hendrey, G., Muniz, I. P., and Snekvik, E., ' 'Effects of Acid Precipitation on Freshwater Organisms, *Impact of' Acid Precipitation on Forest and Freshwater Ecosystems in Norway,* F. Braekke (ed.), SNSF Project, NISK 1432 Aas-NLH, Norway, 1976.
17 Pfeiffer, M. H., and Festa, P. J., "Acidity Status of Lakes in the Adirondack Region of New York in Relation to Fish Resources, Progress Report, Department of Environmental Conservation, New York State, Albany, 1980.
18 Schofield, C. L., "Lake Acidification in the Adirondack Mountains of New York: Causes and Consequences, " *Proc. 1st Int. Symp. on Acid Precipitation and the Forest Ecosystem,* USDA Forest Service General Technical Report NE-23, 477, 1976.
19. Beamish, R. J., ' 'The Loss of Fish Populations From Unexploited Remote Lakes in Ontario, Canada, as a Consequence of Atmospheric Fallout of Acid, *Water Res.* 8:85-95, *1974;* Beamish, R. J., "Acidification of Lakes in Canada by Acid Precipitation and the Resulting Effects on Fishes, *Water, Air, Soil Pollut.* 6:501 *-514, 1976;*

99-413 0 - 84 - 15 : QL. 3

and Beamish, R. J., and Harvey, H. H., ' 'Acidification of the La Cloche Mountain Lakes, Ontario and Resulting Fish Mortalities, ')J. *Fish. Res. Board Can.* 29:1 *131-1143, 1972.*

20. Watt, W. D., ' 'Present and Potential Effects of Acid Precipitation on the Atlantic Salmon in Eastern Canada, *Acid Rain and the Atlantic Salmon,* Special Publications Series of the International Atlantic Salmon Foundation, No. 10, 1981.
21. Herrmann, R., and Baron, J., "Aluminum Mobilization in Acid Stream Environments, Great Smoky Mountains National Park, U. S.A., " *Proc. Int. Conf. Ecol. Impact of Acid Precipitation,* D. Drablos and A. Tollan (eds.), SNSF Project, Norway, 1980.
22. Muniz, I. P., and Leivestad, H,, "Acidification—Effects on Freshwater Fish, " *Proc. Int. Conf. Ecological Impact Acid Precipitation,* D. Drablos and A. Tollan (eds.), SNSF Project, Norway, 1980; and Schofield, C. L., and Trojnar, J. R., "Aluminum Toxicity to Brook Trout (*Salvelinus fontinalis*) in Acidified Waters, *Polluted Rain (New* York: Plenum Press, 1980).
23 Farmer, G. J., Goff, T. T., Ashfield, D., and Samant, H. S., "Some Effects of the Acidification of Atlantic Salmon Rivers in Nova Scotia, " Can. *Tech. Rep. Fish. Aquat. Sci., No. 972, 1980.*
24 Pough, F. H., ' 'Acid Precipitation and Embryonic Mortality of Spotted Salamanders, *Ambystoma Maculatum*,'' *Science* 192:68-70, *1976;* and Stirjbosch, H., "Habitat Selection of Amphibians During Their Aquatic Phase, " *Oikos* 33:363-372, 1979.
25. Okland, K. A., "Ecology and Distribution of Acellus Aquaticus (L) in Norway, Including Relation to Acidification in Lakes, " SNSF Project, IR 52/80, 1432 Aas-NLH, Norway, 1980; and Wiederholm, T., and Eriksson, L., "Benthos of an Acid Lake, " *Oikos* 29:261-267, 1977.
26. Okland, J., "Om Fursuring av Vassdrag og Betydningen av Surhetsgraden (pH) for Fiskens Naeringsdyr: Ferskvann, " Fauna 22: 140-147, 1969; and Svardson, G., "Inform. Inst. Freshw. Res. Drottingholm' (Cited in Almer, et al., 1978), 1974.
27 Almer, B., Dickson, W., Ekstrom, C., and Hornstrom, E., "Sulfur Pollution and the Aquatic Ecosystem, " *Sulfur in the Environment: Part II Ecological Impacts,* J. O. Nriagu (cd.) (New York: John Wiley & Sons, Inc., 1978),
28. Kwiatkowski, R. E., and Roff, J. C., "Effects of Acidity on Phytoplankton and Primary Production of Selected Northern Ontario Lakes, " *Can, J. not.* 54:2546-2561, 1976.
29. Dickson, W., "Some Effects of the Acidification of Swedish Lakes, " *Verh. Int. Verein. Limnol.* 20:851-856, *1978;* and Yan, N. D., "Phytoplankton of an Acidified, Heavy Metal-contaminated Lake Near Sudbury, Ontario, 1973-1977, " *Wat. Air Soil Pollut.* 11 :43-55, 1979.
30 Raddum, G. G., Hobaek, A,, Lomsland, E. R., and Johnson, T., "Phytoplankton and Zooplankton in Acidified Lakes in South Norway, *Ecol. Impact of Acid Precipitation,* D. Drablos and A. Tollan (eds.), SNSF Project, Norway, 1980.
31 Yan, N. D., and Strus, R., "Crustacean Zooplankton Communities of Acidic, Metal-contaminated Lakes Near Sudbury, Ontario, " *Ont.* Min. *Env. Tech. Rep.,* LTS 79-4, 1979.
32 Hendrey, G. R., and Vertucci, F., "Benthic Plant Communities in Acidic Lake Colden, New York: *Sphagnum* and the Algal Mat, *Proc. Int. Conf. Ecological Impact Acid Precipitation,* D. Drablos and A. Tollan (eds.), SNSF Project, Norway, 1980.
33 Harvey, H. H., Pierce, R. C., Dillon, P. J., Kramer, J. P., and Whelpdale, D. M., *Acidification in the Canadian Aquatic Environment: Scientific Criterion for an Assessment of the Effects of Acidic Deposition on Aquatic Ecosystems,* Nat. Res. Coun. Canada Report No. 18475, 1981; Hendrey, G. R., and Wright, R. F., "Acid Precipitation in Norway: Effects on Aquatic Fauna, Proc. 1st Spec. Symp. *on* Atmospheric Contribution to the Chemistry of Lake Waters, Int. Assoc. Great Lakes Res., Orillia, Ontario, Sept. 28-Oct. 1, 1975, *J. Great Lakes Res. 2,* Suppl. 1: 192-207, 1976; Kerekes, J. J., "Summary of the 1980 Environmental Contaminants Control Fund Investigation in the Calibrated Watersheds Study in Kejmkujik National Park, unpublished manuscript, Canadian Wildlife Service, Halifax, Nova Scotia, 1981; and Grahn, O., "Macrophyte Succession in Swedish Lakes Caused by Deposition of Airborne Acid Substances, *Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem,* L. S. Dochinger and T. A. Seliga (eds.), Ohio State University, May 12-15, 1975, USDA Forest Service General Technical Report NE-23, Upper Darby, Pa., Forest Service, U.S. Department of Agriculture, Northeastern Forest Experiment Station, 1976.
34. Hultberg, H., and Grahn, 0,, ' 'Effects of Acid Precipitation on Macrophytes in Oligotrophic Swedish Lakes, *Proc. First. Specialty Symposium on Atmospheric Contribution to the Chemistry of Lake Waters, Internat. Assoc. Great Lakes Res. Sept. 28-Oct. 1, 1975.*
35. Bick, H., and Drews, E. F., ' 'Self Purification and Silicate Communities in an Acid Milieu (Model Experiments), ' *Hydrobiologia* 42:393-402, *1973;* and Traaen, T. S., and Laake, M., ' 'Microbial Decomposition and Community Structure as Related to Acidity of Fresh Waters—An Experimental Approach, SNSF Project, Norway, 1980.

B.2 TERRESTRIAL RESOURCES AT RISK*

The Effects of Ozone on Agricultural Productivity

For over two decades, ozone has been known to harm crops (27). * * Alone, or in combination with sulfur dioxide (SO_2) and nitrogen oxides (NO_x), it causes up to 90 percent of the Nation's air pollution-related crop losses (29). Previous studies estimated that 2 to 4 percent of total U.S. crop production was lost annually, using limited available data and assuming that all areas of the United States just met the current ozone standard. These efforts were limited by the unavailability of field-generated data on crop loss, insufficient data on ozone levels in various parts of the country, and a lack of integration with available crop distribution and productivity data.

OTA's analysis uses National Crop Loss Assessment Network (NCLAN) field-experiment data on the effects of ozone on crops (28), in combination with more recent crop and ozone data, to estimate the effects of ozone on U.S. corn, wheat, soybean, and peanut production.

The selected crops range in susceptibility to ozone from sensitive (peanut) to sensitive/intermediate (soybean) to intermediate (wheat) to tolerant (corn). Among major U.S. agricultural commodities, these four crops represent 62 percent of the acres harvested and 63.5 percent of the dollar value. The analysis compared county-level agricultural data with estimated county-level nonurban ozone concentrations derived from measurements at approximately 300 selected monitoring stations. Actual 1978 crop yields were assumed to represent potential yields minus reductions in productivity due to current levels of atmospheric pollutants including ozone. Data from controlled field experiments were used to develop dose-response functions relating ozone level to crop productivity. The functions were then used to estimate potential gains in productivity achievable by reducing ozone levels to an estimated natural "background" concentration of 25 parts per billion (ppb).

The assessment estimates that in 1978, corn yields would have increased by 2.5 percent, wheat by 6 percent, soybeans by 13 percent, and peanuts by 24 percent if ozone levels had been reduced to natural background levels. As measured by 1978 crop prices, this represents about $2 billion of agricultural productivity. Of the estimated dollar impact, soybeans represent 69 percent, corn 17 percent, wheat 6 percent, and peanuts 8 percent. The Corn Belt States of Illinois, Iowa, and Indiana, plus Missouri, Arkansas, Minnesota, Ohio, Kentucky, North Carolina, and Virginia were estimated to have experienced the greatest agricultural effect.

Crop Response Data

Crop response data were obtained from the 1980 NCLAN Annual Report (77), or from earlier experiments using the methods later adopted for the NC LAN project (22,24,25). Test plants were grown in uniform, open-top field chambers and exposed to carefully controlled ozone levels. Yield data from plants receiving charcoal-filtered air (25 ppb ozone) were used as controls. Three sets of soybean data, four sets of wheat data, and one set each for corn and peanuts were used to estimate quantitative relationships between ozone levels and crop damage.

Crop Yield Data

The Census of Agriculture, conducted approximately every 5 years by the Department of Commerce, develops an extensive national inventory based on responses to mail questionnaires. The 1978 Census of Agriculture provided county-level yield statistics for the surveyed crops. The analysis averaged winter and spring wheat yields together, and excluded sweet corn production from corn yields.

Ozone Data

The U.S. Environmental Protection Agency (EPA) provided estimates of seasonal ozone concentrations for the analysis (75). EPA selected approximatel, 300 from a total of over 500 EPA monitoring stations as regionally representative and free from urban influence. Stations and observations were screened to eliminate those with few or unrepresentative readings. The monitoring stations are irregularly distributed, and large areas of the country lack monitoring data for rural areas. The available data were used to estimate values for counties without monitoring data using a statistical-averaging procedure called kriging. Seasonal averages were calculated as the mean of the growing season months appropriate for each crop (wheat, April-May; corn, peanuts, June-August; and soybeans, June-September). The EPA estimates of average ozone concentration during June to September 1978 are show in chapter 4 (fig. 15).

'This section adapted from Oak Ridge National Laboratory, Environmental Sciences Division, ''An Analysis of Potential Agriculture and Forest Impacts of Long-Range Transport Air Pollutants,'' OTA contractor report, 1983,

● "Citation numbers are keyed to Reference list at back of this section

Regional Impacts

Figures B-5 through B-8 show the general pattern of productivity gains for each crop as potential yield increases (i. e., bushels/acre). Table B-7 summarizes these yield increases (as percentage increases), and their market value at 1978 average crop prices, by State. However, these dollar values do not reflect the potential price effect of the projected yield increases. Since increasing crop production would tend to lower crop prices, the dollar values in table B-7 should only be considered a surrogate for ozone-related crop damage; the dollar values allow comparisons of yield increases across all four crops, as well as comparisons of potential State-level productivity increases.

Projections of Economic Effects If Ozone Levels Are Reduced in the Future

If ozone levels are reduced, the cost of producing an ozone-sensitive crop will decrease, because the same amount of land, fertilizer, labor, etc., will result in greater crop yields. But the economic effects of reducing ozone levels also depend on how farmers and consumers react to these changes. Farmers could, for example, choose to grow the same amounts of these crops as before, reducing their inputs of land, fertilizer, and labor. Alternatively, they could increase their production, making greater crop supplies available in the marketplace, though presumably at somewhat reduced crop prices.

Analysts at the U.S. Department of Agriculture (USDA) used two econometric models to estimate how OTA's projected yield increases might affect farmers and consumers (80). The models assessed the potential effect of eliminating half the manmade ozone over a 10-year period (i.e., reducing ozone concentrations to the midpoint between measured 1978 levels and the estimated natural background level of 25 ppb by the early 1990's).

One of the models focuses primarily on domestic agricultural trends and policies; it projected that increasing the productivity of these three crops would cause supplies to increase moderately. However, it also projected these increases to cause proportionately larger declines in crop prices, reducing net farm income significantly, while inducing only marginal declines in the Consumer Price Index for food. The second model was designed primarily to assess international trends in agricultural production. While it also projected a moderate increase in U.S. supplies of corn, wheat, and soybeans, changes in production levels had significantly different economic repercussions. Estimated price reductions and supply increases were approximately in balance; supply increases outweighed price declines for corn and soybeans, while price declines were proportionately larger than supply increases for wheat. Gross farm receipts for the three crops overall were estimated to increase slightly. The two models provide a qualitative perspective on the complex relationship between pollution and the agricultural sector of the economy; the economic effect of potential ozone reductions depends heavily on both farmer response and Federal agricultural policy.

Effects of Acid Rain on Agricultural Crops

Because several major U.S. agricultural regions experience elevated levels of acid deposition, researchers are attempting to determine whether acid deposition affects crop productivity. Crops are more likely to be damaged through direct contact with acid deposition on aboveground portions of plants than through soil-related effects. However, some soil-mediated effects—e.g., changes in nutrient availability, microbial activity, or metal toxicity—might also be important.

Research on how acid deposition affects crops has advanced about as far as research on ozone effects in the late 1960's. Acid deposition is a mixture of chemicals; plants respond not only to the hydrogen ions (acidity) but also to sulfate and nitrate ions that can act as fertilizers. Moreover, some researchers hypothesize interactions with other physical and biotic causes of plant stress (e. g., air pollution and pests), but little definitive evidence exists on which to base conclusions.

Mechanisms of Acid Rain Effect on Vegetation

No direct, visible injury to vegetation **in** the **field** has been demonstrated to result from exposure to ambient acid deposition. Rather, information about effects comes from a wide variety of approaches involving, in most instances, some form of rain ''simulation. Adding sulfate and nitrate to soil-plant systems can have both positive and negative effects. Each system's response is affected by: 1) precedent conditions (e. g., soil nutrient status, plant nutrient requirements, plant sensitivity, and growth stage); and 2) the total loading or deposition of the critical ions (nitrate, sulfate, and hydrogen ions).

Concentrations of hydrogen ions equivalent to those measured in highly acidic rainfall events (i. e., pH less than about 3), have caused tissue lesions on a wide variety of plant species in greenhouse and laboratory experiments. This visible injury is reported to occur at a threshold of between pH 2.0 and 3.6. No evidence at the present time suggests that hydrogen ion inputs have any beneficial effect.

Table B-7.— Estimated Crop Gains (percentage increase and millions of 1978 dollars) Due to Ozone Reduction—Based on 1978 Crop and Ozone Data

	Wheat		Corn		Soybeans		Peanuts	
	Percent increase	Millions of dollars	Percent increase	Millions of dollars	Percent increase	Millions of dollars	Percent increase	Millions of dollars
Alabama	8.0	—	2.7	1	13.3	28	19.5	21
Alaska	—	—	—	—	—	—	—	—
Arizona	—	—	—	—	—	—	—	—
Arkansas	5.6	1	4.5	—	18.8	132	—	—
California	—	—	2.3	2	—	—	—	—
Colorado	7.6	12	3.0	5	—		—	—
Connecticut	—	—	0.0	—	—	—	—	—
Delaware	2.0	—	3.0	1	12.0	6	—	—
Florida	—	—	1.2	—	9.2	5	14.9	5
Georgia	8.0	1	2.7	5	15.8	29	22.3	72
Hawaii	—	—	—	—	—	—	—	—
Idaho	—	—	—	—	—	—	—	—
Illinois	5.3	5	2.6	68	13,0	262	—	—
Indiana	5.2	3	3.0	42	13.7	123	—	—
Iowa	5.9	—	2.3	73	11.3	200	—	—
Kansas	4.8	33	2.8	10	9.9	17	—	—
Kentucky	3.7	1	2.4	6	12.8	30	—	—
Louisiana	7.3	—	2.3	—	10.8	54	—	—
Maine	—	—	—	—	—	—	—	—
Maryland	2.0	—	3.4	4	14.1	11	—	—
Massachusetts	—	—	—	—	—	—	—	—
Michigan	4.0	2	1.6	7	6.3	9	—	—
Minnesota	4.9	3	1.1	15	9.6	76	—	—
Mississippi	6.7	—	3.7	—	18.0	89	—	—
Missouri	4.5	4	2.7	11	12.7	120	—	—
Montana	0.9	—	—	—	—	—	—	—
Nebraska	6.2	13	2.1	32	8.4	21	—	—
Nevada	6.3	—	—	—	—	—	—	—
New Hampshire	—	—	—	—	—	—	—	—
New Jersey	3.0	—	1.9	.	9.4	3	—	—
New Mexico	10.2	2	3.6	—	—	—	—	—
New York	5.5	—	2.1	2	—	—	—	—
North Carolina	7.2	1	4.1	10	20.6	48	35.9	34
North Dakota	5.3	—	0.7	—	—	—	—	—
Ohio	4.6	5	2.8	22	12.1	97	—	—
Oklahoma	4.7	17	3.0	—	17.9	6	26.3	10
Oregon	1.5	—	—	—	—	—	—	—
Pennsylvania	5.6	1	2.5	7	10.1	2	—	—
Rhode Island	0.0	—	—	—	0.0	—	—	—
South Carolina	8.3	—	4.1	2	21.7	37	35.9	2
South Dakota	5.4	3	1.3	5	8.1	6	—	—
Tennessee	4.9	1	2.9	3	13.2	43	—	—
Texas	7.3	12	2.9	7	11.5	12	12.7	10
Utah	7.8	—	3.7	—	—	—	—	—
Vermont	—	—	—	—	—	—	—	—
Virginia	3.2	—	3.6	4	19.1	15	38.9	21
Washington	1.9	—	—	—	—	—	—	—
West Virginia	3.9	—	2.1	—	—	—	—	—
Wisconsin	6.6	—	2.3	15	12.0	5	—	—
Wyoming	7.5	1	3.0	—	—	—	—	—
United States	5.3	125	2.4	361		1,485	23.8	175

SOURCE: Oak Ridge National Laboratory, 1983.

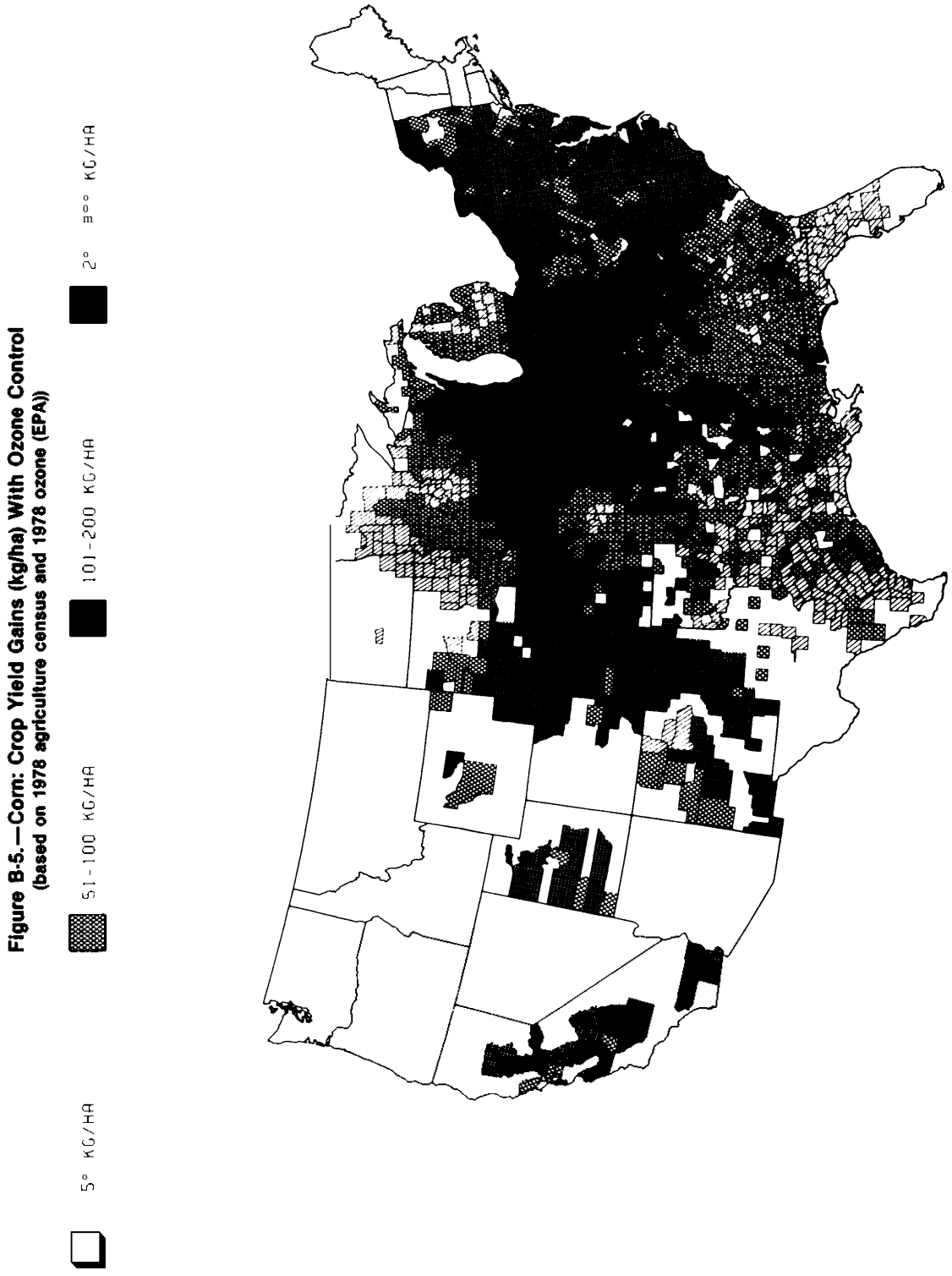


Figure B-5.—Corn: Crop Yield Gains (kg/ha) With Ozone Control (based on 1978 agriculture census and 1978 ozone (EPA))

SOURCE: Oak Ridge National Laboratory, 1983.

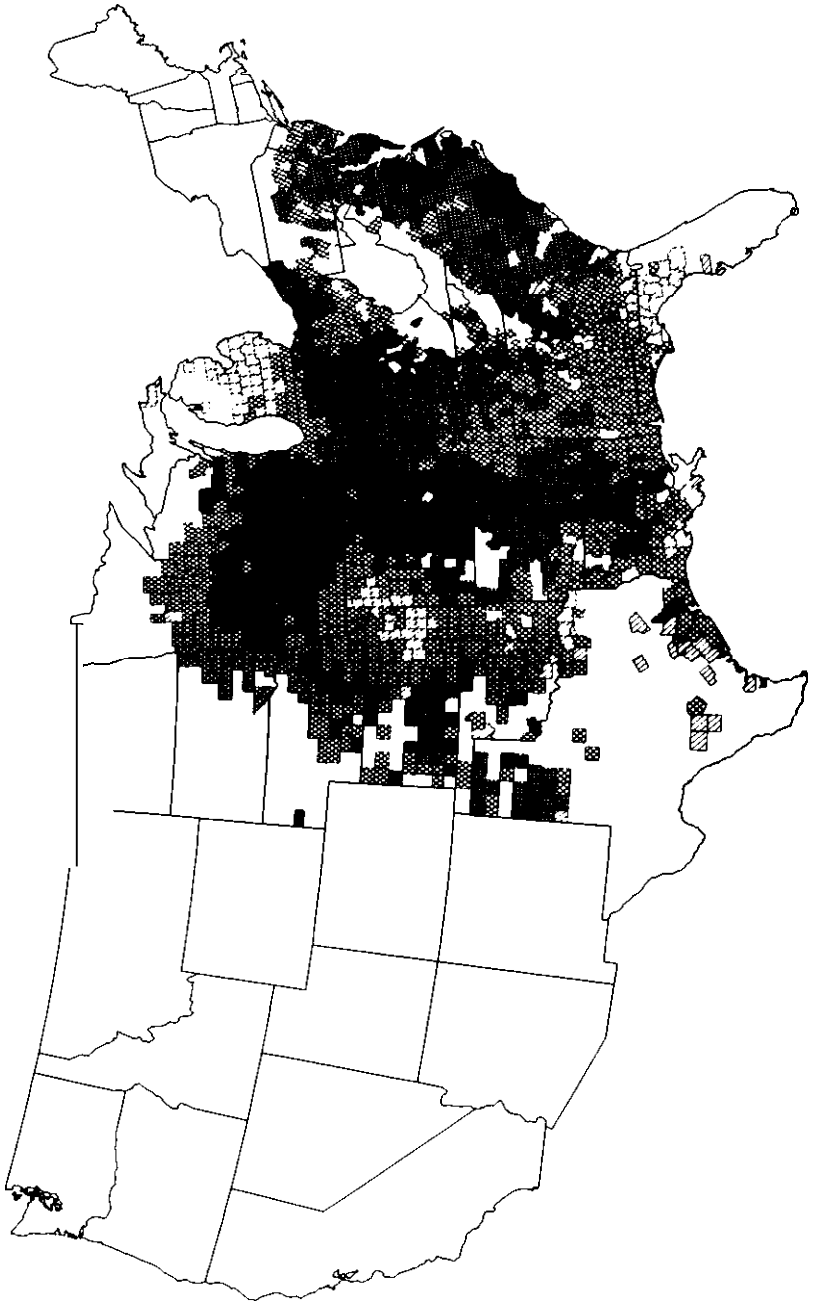


Figure B-6.—Soybeans: Crop Yield Gains (kg/ha) With Ozone Control
(based on 1978 agriculture census and 1978 ozone (EPA))

SOURCE: Oak Ridge National Laboratory, 1983.

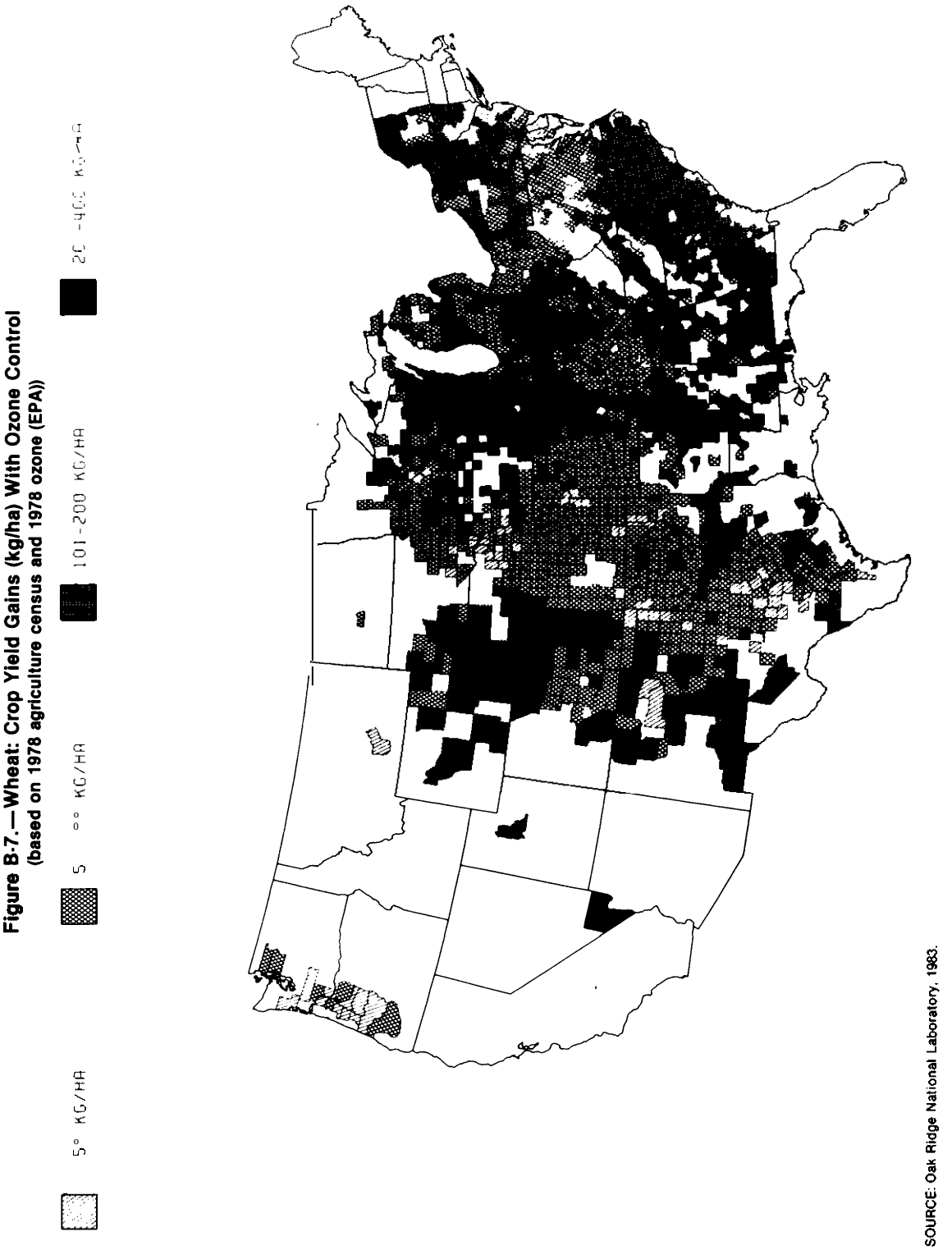


Figure B-7.—Wheat: Crop Yield Gains (kg/ha) With Ozone Control (based on 1978 agriculture census and 1978 ozone (EPA))

SOURCE: Oak Ridge National Laboratory, 1983.

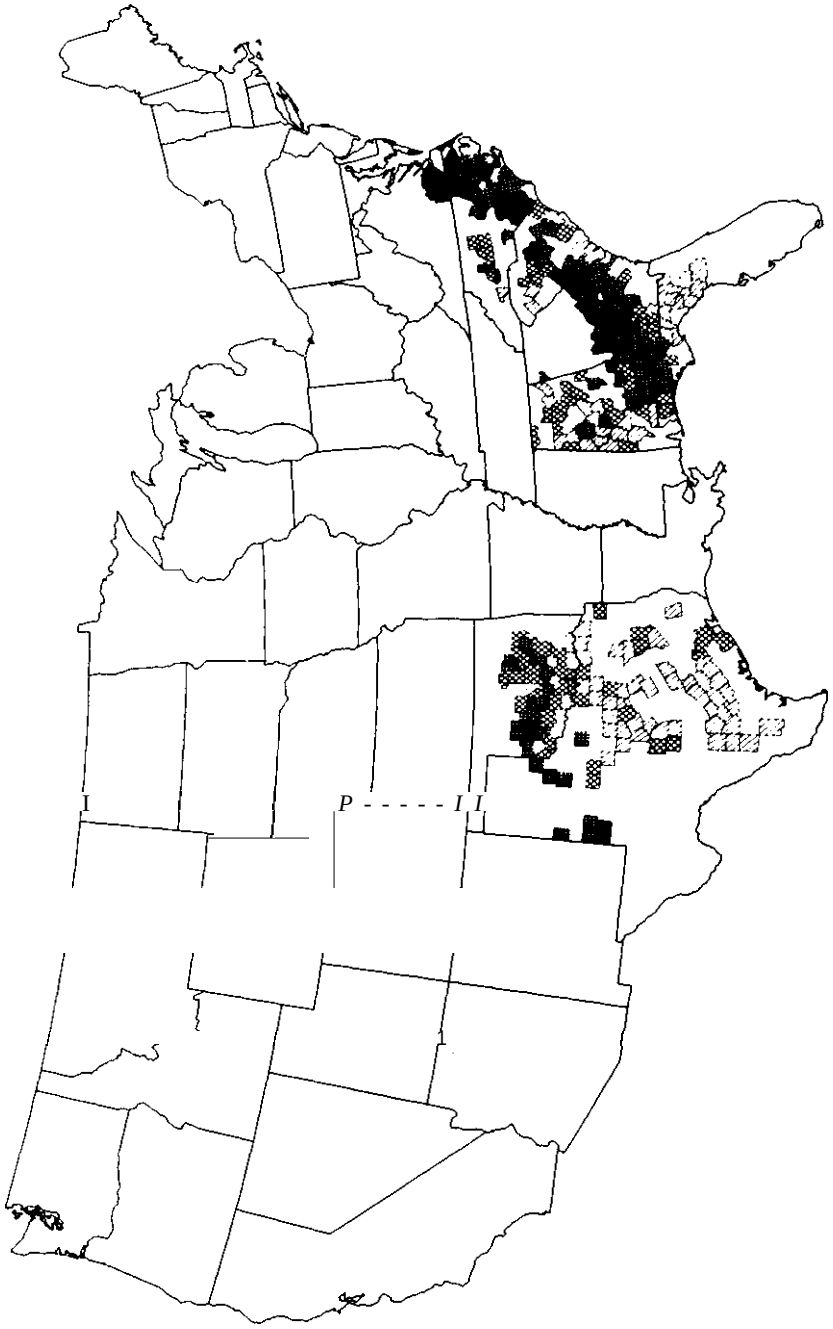


Figure B-8.—Peanuts: Crop Yield Gains (kg/ha) With Ozone Control
(based on 1978 agriculture census and 1978 ozone (EPA))

SOURCE: Oak Ridge National Laboratory, 1983.

Recent research has found that vegetation is extremely responsive to the sulfur and nitrogen inputs in acid precipitation. Evidence from studies of field-grown soybeans (34) and forest tree species (2, 119) indicate an apparent positive growth response to the sulfur and nitrogen in simulated acid rain. Other work suggests that sulfur may have been a limiting factor in the nutrition of experimental lettuce plots (37).

Pollutant deposition theoretically could affect soil-plant systems over the long term through potential soil changes—e.g., loss of calcium and magnesium or release of toxic metals. However, since croplands are heavily managed and fertilized, such soil-related effects due to acid deposition are unlikely.

Results of Field and Laboratory Studies

Several investigators have performed dose-response experiments on a variety of plant species. Thresholds for direct, visible injury to greenhouse foliage subjected to simulated acid rain typically are about pH 3.1 (36). However, field trials using the same treatment solutions under both greenhouse and field situations yield significantly different estimates of species sensitivity.

Experimental evidence suggests that a plant's "wetability' is an important factor in its response to acid deposition. Comparisons between studies of relatively wetable, nonwaxy bean cultivars (19,38,83) and studies of very waxy citrus leaves (26) show that the bean cultivars have a threshold of between pH 3.1 and 3.5 for developing foliar lesions, while a greater than 400-times increase in hydrogen ion concentration—to near pH 2.0—is required to induce visible symptoms in the citrus leaves. Waxy leaves appear to minimize the contact time for acid solutions. Table B-8 summarizes results of field experiments that applied simulated acid rain to nine crops: alfalfa, beet, corn, fescue, kidney bean, mustard green, radish, soybean, and spinach. The table lists effects on crop growth or yield rather than visible injury. No consistent trends are observed. For example, experiments on different types of soybeans resulted in positive, negative, and no growth effects. For both alfalfa and mustard green, altering the chemical composition of the acid rain simulant (but keeping the pH constant) drastically altered experimental results. Further complicating interpretation of these data, research has shown that the experimental procedures used to apply acid rain simulants also can affect results (18).

To summarize available information on how acid deposition affects crops: 1) visible injury thresholds for acid precipitation lie between pH 2.0 and 3.6, depending on species, and may vary from pH 3.0 to 3.6 within the same species (e. g., bean); 2) total dose of hydrogen ions appears to be most clearly related to visible injury; and 3) growth effects in the absence of visible injury have been reported at a threshold of between pH 3.5 and 4.0, but sulfur and nitrogen in the precipitation may cause positive net growth effects, depending on soil nutrient status, buffering capacity, other growth conditions, and plant nutrient requirements.

Relationship of Acid Rain to Overall Crop Damage From Pollutants

Because acid deposition occurs throughout the Eastern United States and Canada, vegetation is commonly exposed both to gaseous pollutants such as ozone and sulfur dioxide, and to wet deposition of acidic substances. Little information is available to evaluate how plants respond to the combined effects of wet- and dry-deposited pollutants.

The foliage of vegetation is wetted by rain, fog, or dew formation during significant portions of the growing season in midlatitude temperate climates. During these periods, leaf surfaces more readily take up dry-deposited gases. For example, researchers found that as SO_2 dissolved in the dew on leaf surfaces, the acidity of the dew increased, suggesting the potential for dry-deposited acidic pollutants to react directly with wet vegetation surfaces (103).

Preliminary work suggests that acid deposition may interact with other pollutants. One researcher observed a significant growth reduction at harvest in plants intermittently exposed to ozone in addition to receiving four weekly exposures to rainfall of pH 4.0 (85). Another demonstrated that ozone depresses both growth and yield of soybeans under three different acid rain treatments, and that the depression was greatest with the most acidic rain (36). Experiments on field-grown soybeans found that simulated acid precipitation (pH 3.1) appeared to lessen plant response to SO_2 (34). The mechanisms of interaction are currently under investigation, but unknown.

Effects of Multiple Pollutants on Forests

One-third of the total land area of the United States is forested; two-thirds of that area—approximately 400 million acres—is classed as commercial timberland. Nearly three-quarters of the country's commercial timberland is located in the Eastern United States, distributed about equally between the North and South sections (fig. B-9). Nearly 80 percent of New England, and greater than 40 percent of the Atlantic Coast States, are forested.

Scientists have recently discovered productivity declines in several tree species throughout the Eastern United States from New England to Georgia. Acid dep-

Table B-8.—Field Research on Effects of Acid Precipitation on Crop Growth and Yield

Species/variety	Test pH	As compared to:	Effect
Alfalfa	3.0, 3.5,	Control: 5.6	No effect on yield
	4.0[a]	Control: 5.6	No effect; 9°/0 greater yield
Beet	2.7, 3.1, 4.0	Ambient: 4.06	Lower number of marketable roots
	5.7	Ambient: 4.06	10°/0 greater shoot growth, 16°/0 greater yield
Corn	3.0, 3.5	Control: 5.6	No effect on yield or growth
	4.0	Control: 5.6	9°/0 lower yield, no effect on growth
Fescue	3.0	Control: 5.6	No effect on yield
	3.5,4.0	Control: 5.6	19°/0, 24°/0 greater yield
Kidney bean	3.2	Control: 6.0	No effect on yield or growth
Mustard green	3.0[a], 4.0a	Control: 5.6	No effect; 31 to 33% lower yield
	3.5	Control: 5.6	No effect on yield
Radish "Champion"	2.8	Control: 5.6	13 to 17°/0 higher root weight
	3.5	Control: 5.6	7 to 11 °/0 higher root weight
	4,2	Control: 5.6	3 to 7°/0 higher root weight
	5.6	Ambient: 3.8	No effect; 12°/0 lower root weight
Radish "Cherry Belle"	3.0,4.0	Control: 5.6	No effect on yield or growth
	3.5[a]	Control: 5.6	No effect; 25°/0 greater yield
Radish "Cherry Belle"	2.7, 3.1, 4.0	Control: 5.7	No effect on yield or growth
Soybean "Amsoy"	2.3	Ambient: 4.1	No effect on yield, lower pods/plant
	2.7	Ambient: 4.1	11 % lower seed weight, lower seeds and pods/plant
	3.1, 4.0	Ambient: 4.1	No effect on yield or growth
Soybean "Amsoy"[b]	2.7[a]	Control: 5.6	3 to 11 % lower yield
	3.3[a]	Control: 5.6	7 to 17°/0 lower yield
	4.1[a]	Control: 5.6	8 to 23°/0 lower yield
Soy bean "Benson"	2.8	Control: 4.0	32°/0 greater yield, 17°/0 greater seed size
	3.4	Control: 4.0	No effect on yield, 8°/0 smaller seed size
Soybean "Davis"	2.8, 3.2, 4.0	Control: 5.3	No effect on yield or growth
	2.4, 3.2, 4.1	Control: 5.4	No effect on yield or growth
Soybean "Wells"	3.06	Control: 5.6	No effect on yield, 4°/0 greater weight/seed
	5.6	Ambient: 4.1	No effect on yield, 4% greater weight/seed
Soybean "Williams"	2.8	Control: 4.0	No effect on yield, 17°/0 smaller seed size
	3.4	Control: 4.0	No effect on yield, 22°/0 greater seed size
Spinach	3.0, 3.5, 4.0	Control: 5.6	No effect on yield or growth

aDifferent acid rain simulants or treatment methods produced different results.
bSee reference 18 to text of this section.

SOURCE: Modified from U.S. Environmental Protection Agency, "Effects on Vegetation," *The Acid Deposition Phenomenon and Its Effects,* **Critical** *Assessment Review Papers,* **Public Review Draft, 1983, except as noted above.**

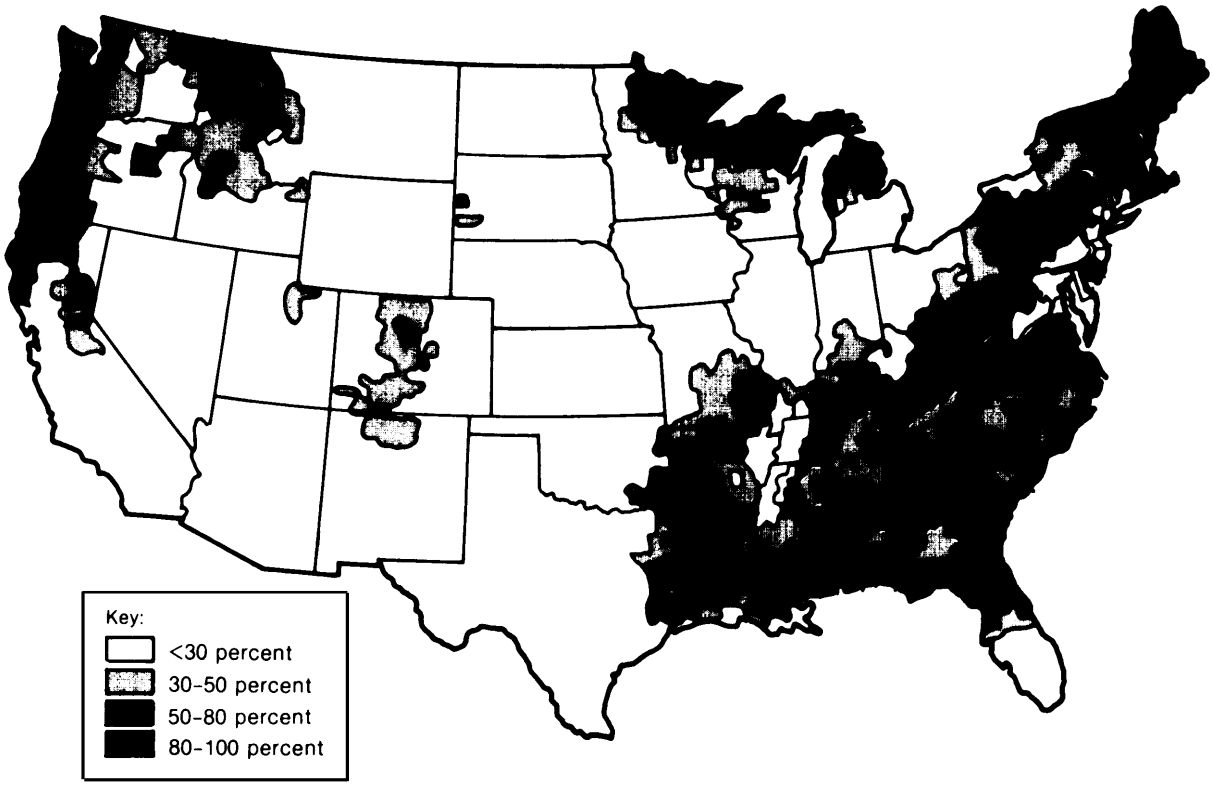
osition, ozone, heavy-metal deposition, drought, severe winters or a combination of these are possible causes under investigation.

By coring trees and measuring the thickness of annual growth rings, scientists have observed marked reductions in productivity beginning about 1960 in red spruce, shortleaf pine, and pitch pine. Corings from about 30 other species at 70 sites throughout the East are currently being analyzed to determine the geographic extent and severity of the problem. Routine measurements of tree growth by the U.S. Forest Service have shown productivity declines in loblolly pine and shortleaf pine during the 1970's in the Piedmont region of South Carolina and Georgia. Again, the cause of these declines is not yet known, but air pollution is a possible factor.

Air pollutants can influence plant health through a complex process that depends not only on the level of pollution and duration of exposure but also on environmental factors that influence the plant's overall response as a living organism under stress. As with all stress-inducing agents, air pollutants may initiate changes within plant metabolic systems that cause extensive physiological modifications; sufficient change may lead to visible symptoms. In some instances, adding low pollutant levels to a plant's environment may induce a fertilizer-like response. This phenomenon has been analyzed in agronomic crops; however, no studies have shown beneficial effects on natural ecosystems.

Continual exposure to pollutants such as ozone and sulfur dioxide can cause tree death. Other contributing or mitigating factors also may be involved (i. e., abiotic or biotic disease-inducing agents or insect attack). Depending on the tree species, the seasonal stage of growth, pollutant dose, and environmental conditions, many forms of injury, varying widely in impact, may occur. A given plant may exhibit symptoms of acute and chronic injury simultaneously. However, injury does not necessarily imply damage (i. e., economic loss).

Figure B-9.—Percent of Land Area Capable of Commercial Timber Production



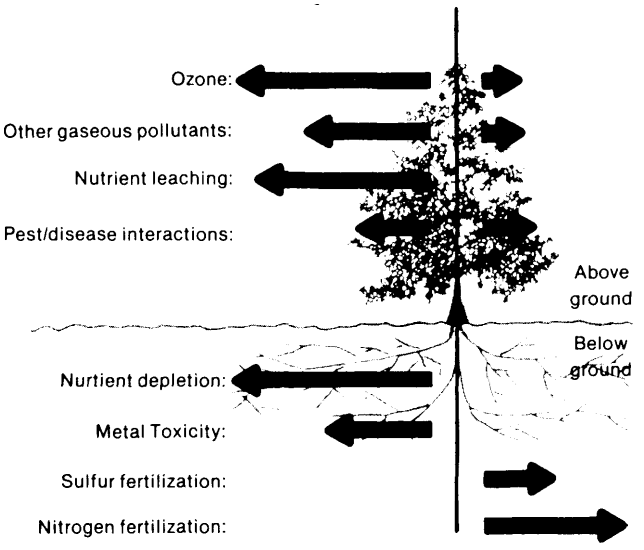
aThe U.S. Forest Service deflnes commercial timberland as lands capable **of** producing greater than 20 Cubic **feet of industrial roundwood per acre per year, in natural stands.**
SOURCE: Oak Ridge National Laboratory from **u.s.** Forest Service inventory data.

The potential effects of acid deposition and gaseous pollutants (e. g., ozone) on forest productivity can be discussed only qualitatively at present. Figure B-10 summarizes the various mechanisms by which such a combination of pollutants might affect forest productivity. The top part of the diagram illustrates positive and negative effects on exposed vegetation; the bottom part of the diagram illustrates positive and negative effects on vegetation through soil processes. For example, each of the gaseous pollutants—ozone, SO_2, and NO_x—has a predominantly negative effect on vegetation. Acid deposition may have both positive and negative effects-fertilizing the soil with sulfur and nitrogen, but potentially leaching nutrients from leaves and releasing toxic aluminum from the soil.

Figure B-10 shows the **net** effect on the growth of vegetation as the sum of a series of positive and negative effects. Site-specific factors that control plant responses to any individual mechanism are likely to determine the net effect on plant productivity, assuming that different mechanisms do not interact to produce additional effects.

The greatest potential for negative pollutant impacts on trees appears to occur in the commercial forests of the Southeastern Coastal Plain, the Mississippi River Valley, the Appalachian Mountain chain, and the upper Ohio River Valley. These regions experience both high concentrations of ozone and elevated levels of acid deposition. In each of these areas, nitrogen inputs to forests would be expected to partially offset negative impacts, while sulfur inputs currently exceed forest growth requirements and probably have neither a significant positive or negative influence at this time.

To summarize the potential for long-term forest-productivity effects from both acid deposition and gaseous pollutants, at the present time OTA can state only that such interactions might occur and that their probability of occurrence is greatest in those regions of the Eastern United States outlined above. The mechanisms involved and the relative importance of those mechanisms to forest growth response must be studied further in order to better describe and eventually quantify these potential effects.



SOURCE: Office of Technology Assessment.

Implications of Potential Forest Productivity Declines Due to Air Pollution

If air pollution is shown to significantly affect the productivity of commercially forested timber species, potential long-term effects on forestry and related industries could be of concern. OTA used in-house information and analyses to identify significant factors about the current forest industry and how it might be affected by potential forest productivity declines due to air pollution.

It is estimated that improved management practices on suitable lands could double sustainable timber harvest levels on over 90 percent of forestland in the Eastern United States. Thus, significant **potential** for offsetting future forest productivity declines exists.

However, if timber harvest levels do not increase, potential forest-productivity losses due to air pollution could be of particular significance for regional timber markets in the South. Lack of softwood reforestation on many private nonindustrial forest lands over the past two decades may decrease softwood-timber harvests in the South, beginning about 1995. Timber supplies in the Northeastern United States appear to be adequate for the foreseeable future. Productivity declines, whether of regional or local scale, could threaten the economic viability of individual lumbermills and papermills. Significant reductions in harvests over a sustained period could cause mill closures; papermills are particularly vulnerable, since they represent large capital investments, and must operate very close to capacity (in general, over 90 percent) to break even.

Potential losses in timber production in the Northeast and South, if realized, could alter opportunities to increase forest-product exports, and could, at the extreme, result in increasing imports of timber from the Canadian Northwest.

Effects of Ozone on Forest Productivity

Considerable literature is available to describe ozone effects on forest vegetation. Most studies examined foliar (leaf) injury rather than yield loss. Table B-9 lists tree species that have been determined to be sensitive, of intermediate sensitivity, and tolerant of ozone. However, researchers caution against overreliance on these relative rankings, because the individual experiments varied in study methods used (exposure chamber, ambient air), age of trees, and type of response measured (injury, growth).

Most of the few studies examining yield loss exposed forest tree seedlings to ozone under controlled laboratory or greenhouse conditions. One field study, how-

Table B-9.—Relative Susceptibility of Trees to Ozone Damage

Sensitive	Intermediate	Resistant
Tree-of-Heaven	**Boxelder**	**Balsam fir**
juneberry	**eastern redbud**	**white fir**
white ash	**Japanese larch**	**sugar maple**
swamp ash	**incense cedar**	**Norway maple**
honey locust	sweetgum	European white birch
European larch	knobcone pine	flowering dogwood
tulip poplar	lodgepole pine	European beech
jack pine	short leaf pine	American holly
coulter pine	South Florida slash pine	black walnut
Jeffrey pine	sugar pine	western juniper
Austrian pine	pitch pine	swamp tupelo
ponderosa pine	eastern white pine	Norway spruce
monterey pine	Scotch pine	white spruce
loblolly pine	Torrey pine	blue spruce
Virginia pine	scarlet oak	red pine
American sycamore	pin oak	digger pine
Japanese poplar	black oak	Rocky Mountain Douglas fir
black cottonwood	common lilac	common pear
quaking aspen	Chinese elm	shingle oak
white oak		bur oak
European mountain ash		English oak
lilac		northern red oak
		black locust
		redwood
		giant sequoia
		northern white cedar
		American basswood
		littleleaf linden
		eastern hemlock

SOURCE: D. D. Davis and H. D. Gerhold, "Selection of Trees for Tolerance of Air Pollutants," *Better Trees for Metropolitan Landscapes Symposium Proceedings,* U.S. Forest Service General Technical Report, NE-22:61-66, 1976.

ever, has measured yield reductions in mature white pine in the Blue Ridge Mountains of Virginia.

The study compared annual radial-increment growth in tolerant, intermediate, and sensitive varieties of white pine *(Pinus strobus) (6).* Observed within-species variations in ozone-induced foliar injury were used to classify trees into the three sensitivity categories. The trees were then compared to determine how much less growth had occurred in the sensitive and intermediate varieties than in their tolerant counterparts. Growth in the sensitive and intermediate varieties was reduced by 45 percent and 15 percent for 1 year (1978), by 40 percent and 20 percent over a 10-year period (1968-78), and by 28 percent and 15 percent over a 25-year cumulative period. These figures may be conservative, as they are based on comparisons to ozone-tolerant tree growth in areas of known ozone occurrence (50 to 75 ppb, 7-hour average, May-September yearly).

Several field studies related significant changes in forest ecosystem **response** to ambient oxidant concentrations (88). The San Bernardino Mountain Study documented mortality of sensitive ponderosa *(Pinus ponderosa)* and Jeffrey *(P. Jeffreyi)* pines after bark beetles infested air-pollution-stressed trees (63,65). Air pollution stress appears to be shifting forest species composition toward more tolerant species such as white fir. Other examples of shifts in species composition associated with oxidants or mixtures of air pollutants also have been reported (21,60),

Fate and Effects of Acid Deposition in Forest Ecosystems

Upon entering a forest ecosystem, acidic pollutants such as sulfate and nitrate become part of a chemical system regulated by a variety of natural processes, The chemical constituents of acid deposition should be viewed as an addition to the hydrogen, sulfate, and nitrate ions produced and cycled naturally within forest ecosystems.

This section discusses ways in which atmospherically deposited hydrogen, sulfate, and nitrate ions could affect forest nutrient cycles. The section also examines the fate and effects of deposition in excess of amounts that can be biologically used, or chemically trapped or neutralized by forest soils.

Effects on Forest Sulfur and Nitrogen Status

Acid deposition contains readily usable forms of the essential plant nutrients sulfur and nitrogen. Nitrogen-deficient forests are common throughout the United States, but sulfur-deficient forests are much less common, occurring primarily in the Pacific Northwest (98,99,1 14,120).

Atmospheric inputs of nitrate and ammonium could improve nitrogen nutrition substantially in forests of the North Central and Northeastern States, especially in areas near the eastern Great Lakes. In most areas of the West, atmospheric nitrogen inputs are much less significant when compared to the total nitrogen requirements of Western forests.

The sulfur deposited in some forested areas of the Western United States may be less than that required for optimal growth, but data to quantify how widely this occurs are scanty. Much of the Eastern United States appears to receive inputs equal to or in excess of tree sulfur requirements. Moreover, trees require nearly 15 times as much nitrogen as sulfur, on a weight basis, to synthesize protein. The ratio of nitrogen to sulfur in atmospheric deposition is far from this ideal value throughout the United States, with greater amounts of sulfur than nitrogen deposited over most of the Eastern United States. Thus, it would appear that substantially greater quantities of sulfur are being deposited than can be used as fertilizer over the long term, and that many forests would have to be heavily fertilized, or otherwise enriched in nitrogen, to benefit at all from sulfur deposition (99).

Forests do not depend entirely on atmospheric inputs to meet nutrient requirements, as they recycle nutrients —e. g., by reclaiming them from decomposing leaves. When atmospheric nutrient inputs fail to meet growth requirements and soil-available nutrient supplies are low (as is often the case for nitrogen), recycling processes within forest ecosystems and nutrient translocation from one part of a tree to another help supply nutrients to growing tissues. Thus, while increased atmospheric nitrogen and sulfur inputs might benefit forests limited in those nutrients, under undisturbed conditions atmospheric inputs do not have to equal plant uptake to maintain site fertility. However, to maintain site fertility in harvested forests, inputs must compensate for the amount of nutrients removed by logging.

Effects on Forest Cation Nutrient Status

In addition to supplying some nutrients, acid deposition (and naturally produced acids) can remove other nutrients stored in leaves, the litter layer on the forest floor, or the soil. The hydrogen ions (i. e., the "acidity' of acid deposition can replace or "leach' nutrient cations, * removing these essential nutrients from the forest ecosystem.

Acid deposition can remove essential nutrient cations (e. g., calcium) directly from tree foliage. If the rate of nutrient loss is greater than can be replaced through the roots, nutrient deficiency will result. Scientists do not know which tree species are most susceptible to foliar nutrient loss, or the level of acid deposition at which such loss becomes harmful. For any given species, the rate of loss probably depends on both the total amount and concentration of acid-producing substances (sulfate and nitrate) deposited on leaf surfaces.

Nutrient leaching from soils is somewhat different. No cation leaching will occur unless the acid-producing substances can travel freely through the ecosystem (47). Since forest nitrogen deficiencies are very common and nitrate is taken up readily by forest vegetation (1 ,74), atmospheric nitrate inputs are unlikely to be mobile enough to leach significant amounts of nutrient cations from most forest soils. Sulfate, the other major acid-producing substance in rainfall, can travel through many types of forest soils and is, therefore, of greater concern.

While acid deposition can accelerate cation leaching rates, the magnitudes of these increases must be compared to losses from natural leaching processes. The relative importance of deposition-induced leaching depends on: 1) the amount of acid input at a given site, 2) the rate of soil leaching by natural processes (8, 10,66), and 3) the ability of soils to buffer against leaching (e. g., by "adsorbing" or trapping sulfate onto their surfaces) (46). Furthermore, a number of variables govern how accelerated leaching ultimately affects forest cation nutrient status, most notably: 1) the amount of exchangeable cations, 2) the rate at which nutrients are replaced through mineral weathering (74,9 1), 3) forest cation nutrient requirements, and 4) management practices such as harvesting (44).

If the quantities of soil cation reserves within a forest ecosystem are large relative to leaching rates (e. g., in calcareous soils), a doubling or tripling of leaching rates due to acid rain probably would be of little consequence. If reserves are small (e. g., in highly weathered soils), doubling or tripling of leaching rates may have long-term significance. Soils in which current input levels of acid deposition can significantly deplete nutrient reserves over less than many decades are probably rare, however. Nonetheless, given a sufficiently large input for a sufficient amount **of time,** acid rain must eventually deplete these reserves.

Currently, few forests of the United States have cation deficiencies, although notable exceptions are known in certain forests of the Northeast (90). An intensive

*"Nutrients [hat have the same chemical charge as hydrogen ions, e g., calcium, magnesium, and potassium

study of a central Adirondack Mountain forest indicates that atmospheric sulfate deposition has increased rates of soil nutrient-cation leaching substantially (66). Since these soils are quite low in available cation reserves, the researchers concluded that, "Chronic leaching by [sulfuric acid] combined with internally generated organic acids may represent a real threat to the nutrient status of many Adirondack forest soils' (66). However, the authors acknowledge that total soil cation reserves and weathering rates (or rates at which these reserves become available to trees) are unknown, and that a complete assessment must encompass these factors. Acid rain itself may cause soil weathering rates to increase, potentially offsetting accelerated nutrient leaching to some extent.

Effects of Aluminum Mobilization

Soil scientists have long known that soils release aluminum under sufficiently acid conditions (5, 121). Aluminum is also known to be toxic to plant roots in sufficient concentrations, either killing them directly or interfering with nutrient uptake (especially phosphorus and calcium) (71, 73). Researchers recently found a marked increase in soil aluminum concentrations over a 13-year period in a beech and Norway spruce forest soil at the Soiling site in West Germany (58, 101). They attributed the change to a combination of natural acidifying processes within the forest ecosystem and atmospheric acid inputs. Furthermore, the authors believe that aluminum levels have become toxic to tree roots, posing a situation with ''serious consequences for forestry in Central Europe.

The findings of these West German researchers are cause for concern, but they may not apply to all forest types. Acid and sulfate inputs are very high at the Solling site, as would be necessary to further acidify a soil that was initially very acid. Moreover, species vary widely in their susceptibility to aluminum toxicity. *

Similar declines have been observed in red spruce in the Northeastern United States. However, recent work fails to support the soil aluminum hypothesis in these cases. Specifically, researchers found no changes in soil pH over a 15-year period (1965-80) and no relationship between tree vigor and root or foliar aluminum concentration. The causes for the decline in red spruce are unknown as of this writing. Acid rain, aluminum concentrations, and forest decline, but acid rain (perhaps via other mechanisms) remains one of several working hypotheses under investigation.

It must be emphasized that acid rain effects are site-specific, depending on the amount of acid input and on the vegetation, soils, and nutrient status of the site receiving such inputs. Forest ecosystems in **general** cannot be expected to respond to acid rain in any single way.

The Regional Distribution of Soils at Risk From Acid Deposition

Analysts have proposed and used several sets of sensitivity criteria to define geographical regions most susceptible to acid deposition effects. Each set is based on scientific concepts that aim at particular target organisms or ecosystems (e. g., forests or aquatic ecosystems). Those directed toward aquatic effects emphasize bedrock geology (3 1,67), while those directed toward soils effects emphasize cation exchange capacity (C EC) and base saturation (52,59).

Scientists at Oak Ridge National Laboratory have classified unmanaged (i. e., forest or range) soils according to their sensitivity to three types of acid-deposition-induced changes: 1) losses of essential nutrients such as calcium and magnesium, 2) release of toxic metals such as aluminum, and 3) further acidification.

The classification scheme uses three soil properties: 1) whether the soil adsorbs (chemically traps) sulfate; 2) the soil's cation exchange capacity (CEC); ** and 3) the PH (acidity) of the soil, which also indicates base saturation, i.e., the relative proportion of basic cations (nutrients such as calcium and magnesium) to acidic cations (hydrogen and aluminum).

Table B-10 outlines the relative sensitivities of various soil types; figures B-11 and B-12 describe the chemical exchanges that acid deposition produces in each of these soils. Figure B-13 maps the extent and location of these soils in the Eastern United States. The three types of potential soil changes attributable to acid deposition are discussed separately below.

RELEASE OF ALUMINUM

As shown in table B-10, soils that are naturally acidic (i.e., pH below about 5) and that do not adsorb sulfate, are considered most likely to release toxic metals such as aluminum. Figure B-11 illustrates the mechanism schematically. Sulfate and hydrogen ions from acid deposition reach the soil layer. Because the soil does not trap sulfate, the sulfate is free to move through the soil. The associated hydrogen ion can either: 1) travel with the sulfate, or 2) be exchanged on the soil surface for a base cation (e. g., calcium or magnesium) or an acid

"Researchers report great variations m toxicity thresholds among several tree species, ranging from 10 mg/l Al in solution for a poplar hybrid to 80 to 120 mg/l in oak, birch, and pine *(61)*. Others report Al concentrations in "equ ilibrium soil solution (i. e., solution obtained after extraction of soil with water for 24 hr) of less than 3 mg/l (101) More recently, Al concentrations of nearly 20 mg/l in soil solutions were reported from the spruce stand at Solling (58).

" "The total amount of cations (positively charged ions such as calcium, magnesium, aluminum, and hydrogen) the soil can hold.

Table B-10.—Theoretical Sensitivities of Forest Soils to Acid Deposition

Soil properties		Terrestrial sensitivity to:		
pH	CEC[a]	Base cation loss	Soil acidification (surface soils)	Al solubilization
I. Non-sulfate-absorbing soils				
1. >6	High	High	Low	Low
2. > 6	Low	High	Low-moderate	Low-moderate
3. 5-6	High	High	Moderate	Moderate
4. 5-6	Low	High	High	Moderate
5. < 5	High	Moderate	Moderate	High
6. < 5	Low	Moderate	Moderate	High
IL Sulfate-absorbing soils				
7. >6	High	Moderate	Low	Low
8. > 6	Low	Moderate	Low-moderate	Low
9. 5-6	High	Low	Moderate	Low
10. 5-6	Low	Low	High	Low
11. <5	High	Low	Moderate	Low
12. <5	Low	Low	Moderate	Low

%Cation Exchange Capacity (CEC).
bHigh CEC = above 9.0 **meq/ml, low CEC = below 9.0 meq/ml**

SOURCE: Oak Ridge National Laboratory, 1983.

cation (aluminum or another hydrogen ion). Because aluminum both dissolves most easily and is most plentiful in acid soils (fig. B-11c), these soils release the greatest amounts of aluminum.

Figure B-12 illustrates soil processes in sulfate-adsorbing soils. Because these soils can trap both sulfate and the associated hydrogen ion from acid deposition, less aluminum is released.

Figure B-13 shows the distribution of soils considered susceptible to aluminum release, based on county-level soil data. The medium-grey areas are the naturally acid, nonsulfate adsorbing soils discussed above. These cover New England, and parts of northern New York State, the upper Midwest, and the South. Acid soils that can adsorb sulfate are shaded as light grey. These cover large areas of the South and South Central States. Because soils classified as adsorbing sulfate often do so only in deeper soil layers, the surface layers in these regions still might be susceptible to aluminum release.

SOIL ACIDIFICATION

Soils thought to be sensitive to further acidification are moderately acid (pH about 5 to 6) with low CEC. Such soils occur to a very minor extent in those regions receiving significant inputs of acid deposition. As shown as the darkest areas on figure B- 13, these soils predominate in scattered counties east of the Mississippi (i. e., counties in Illinois, Indiana, Georgia, and Tennessee). Other areas of the East receiving higher deposition levels (e.g., parts of the Adirondacks) probably have some soils of this type, but not in sufficient quantities to constitute a county's predominant soil type.

For these moderately acidic soils, concerns over further acidification include: 1) potential effects on soil biota, 2) release of aluminum if acidity increases to below a pH of about 5, and 3) the loss of nutrients from these soils, as discussed below.

NUTRIENT DEPLETION

As shown in table B-7, those soils most susceptible to nutrient cation (calcium, magnesium, and potassium) loss are soils with a moderate to high pH that do not adsorb sulfate. Again, figures B-11 and B-12 show the mechanisms of nutrient loss. As sulfate and associated hydrogen ions enters the soil layer, the hydrogen ions can be exchanged for base cations. Sulfate-adsorbing soils trap hydrogen ions (fig. B-12), while lower pH soils (e. g., fig. B-11c) exchange most of the hydrogen ions for aluminum and remove fewer nutrient cations.

Of the soils listed as most susceptible to nutrient loss in table B-9, only the moderate pH, nonsulfate adsorbing soils with low CECs have both a high potential for nutrient loss and low enough nutrient levels so that this loss might be significant. These are the same soils discussed above as being susceptible to further acidification, and are shown on figure B-13 as the darkest regions.

Though listed as only moderately susceptible to nutrient loss in table B- 10, naturally acid, nonsulfate-adsorbing soils typically have the lowest quantities of stored nutrient cations. Some of these *areas may* have such low nutrient levels that further loss might affect forest productivity. Such areas might be located within the medium-grey regions shown in figure B-13; how-

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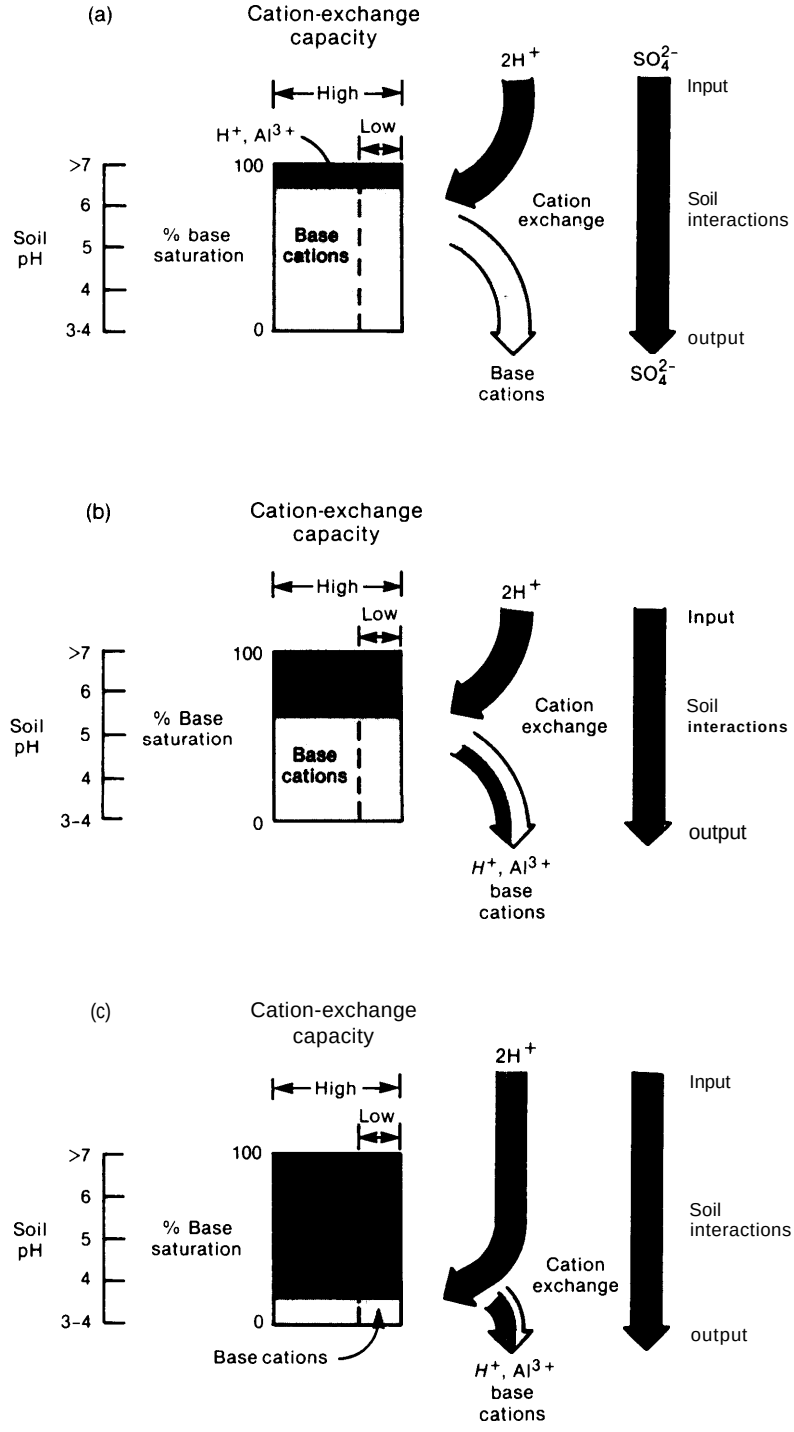
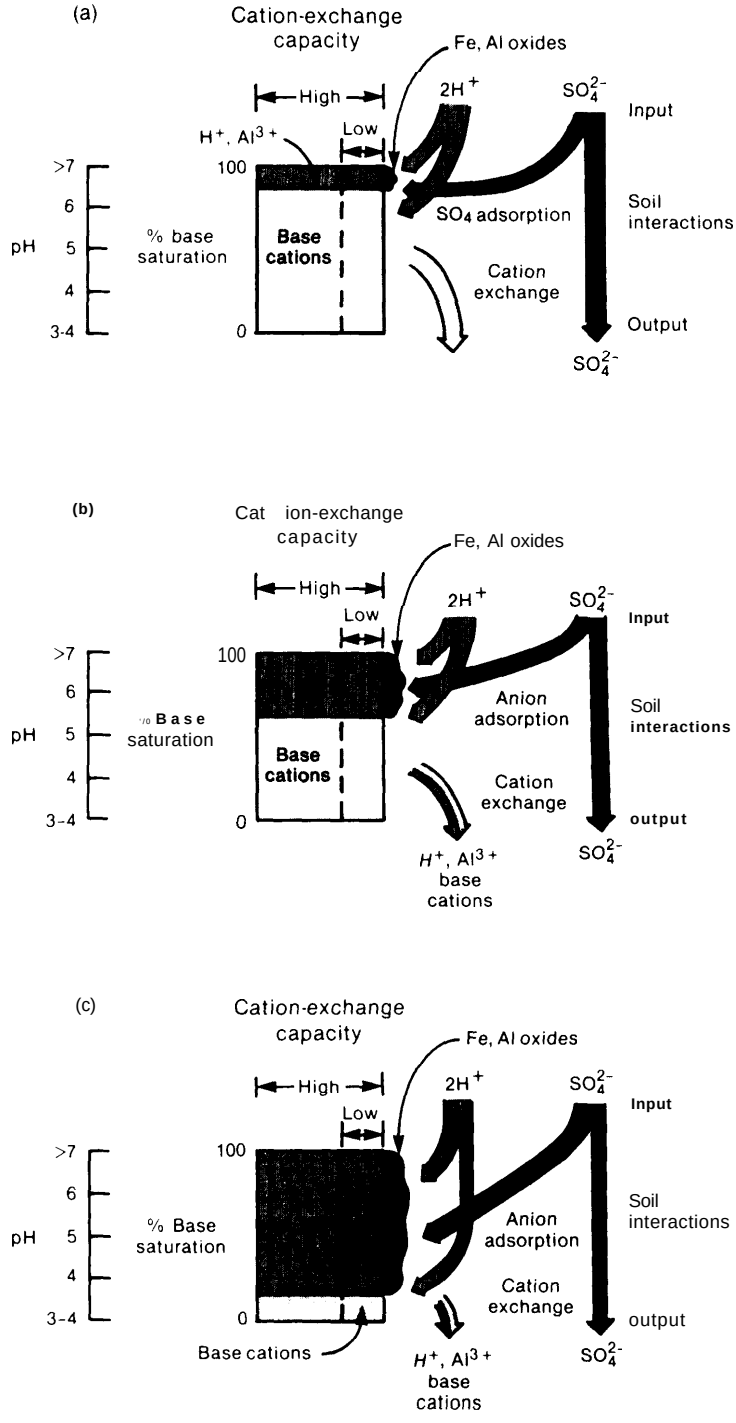
Figure B-n .—Schematic Diagrams of Soil Leaching in Non-Sulfate-Adsorbing Soils



SOURCE: Oak Ridge National Laboratory, 1983.

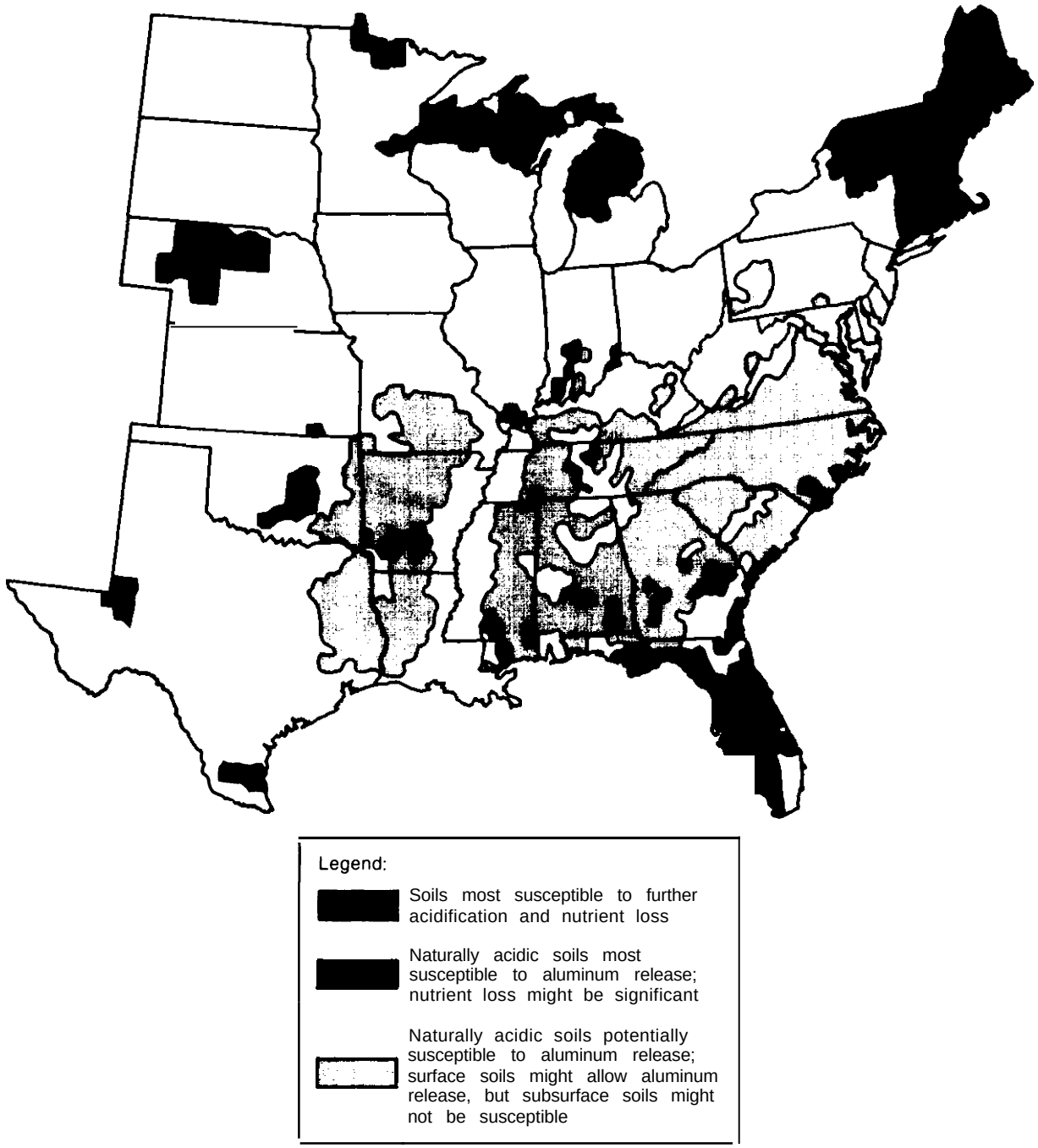
Figure B-12.-Schematic Diagrams of Soil Leaching in Sulfate-Adsorbing Soils



SOURCE: Oak Ridge National Laboratory, 1983.

Figure B-13.-Soil Sensitivity to Acid Deposition (nonagricultural)

Forested and range areas with soils thought to be susceptible to the effects of acid deposition. Shaded areas represent counties in which a susceptible soil type predominates. The three levels of shading correspond to different soil types, and potential effects, rather than to degrees of susceptibility.



SOURCE: Oak Ridge National Laboratory, 1983.

ever, whether nutrient loss rates exceed natural replacement rates from weathering is unknown.

B.2 References

(Numbers are keyed to citations in text)

1. Abrahamson, G., "Acid Precipitation, Plant Nutrients, and Forest Growth, *Ecological Impact of Acid Precipitation,* D. Drablos and A. Tollan (eds.) (Mysen, Norway: Johs. Grefslie Trykkeri A/S, 1980).
2. Abrahamson, G., and Dollard, G. J., "Effects of Acidic Precipitation on Forest Vegetation and Soil, *Ecological Effects of Acid Precipitation, G.* Howells (cd.) (La Jolla, Calif.: Electric Power Research Institute, EPRI 50A77-403, 1979).
3. American Phytopathology Society, "Glossary of Air Pollution Terms and Selected Reference List, *Phytopathol. News* 8:5-8, *1974.*
4. Andersson, F., Fagerstrom, T., and Nilsson, S. I., "Forest Ecosystem Responses to Acid Deposition—Hydrogen Ion Budget and Nitrogen/Tree Growth Model Appreaches," *Effects of* Acid Precipitation *on* Terrestrial Ecosystems, T. C. Hutchinson and M. Havas (eds.) (New York: Plenum Press, 1980).
5. Bache, B. W., "The Acidification of Soils, Effects *of* Acid Precipitation *on* Terrestrial Ecosystems, T. C. Hutchinson and M. Havas (eds.) (New York: Plenum Press, 1980).
6. Benoit, L. F., "Ozone Effects on Long-term Growth and Reproduction in Eastern White Pine, M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, Va., 1981.
7. Brennan, E., and Davis, S. H., "Air Pollution Damage to Austrian pine inNew Jersey, *Plant Dis. Rep.* 51:964-967, *1967.*
8. Cole, D. W., and Johnson, D. W., "Atmospheric Sulphate Additions and Cation Leaching in a Douglas-Fir Ecosystem, Water *Resour. Res.* 13:313-317, 1977.
9. Cost, N. D., "Forest Statistics for the Mountain Region of North Carolina, 1974, USDA Forest Service Resource Bulletin SE-31 (Southeast Forest Experiment Station, Asheville, N.C.), 1975.
10. Cronan, C. W., Reiners, W. A., Reynolds, R. L., and Lang, G. E., "Forest Floor Leaching: Contributions From Mineral, Organic, and Carbonic Acids in New Hampshire Subalpine Forests," *Science* 200:309-311, 1978.
11. Davis, D. D., and Coppolino, J. B., "Relationship Between Age and Ozone Sensitivity of Current Needles of Ponderosa Pine," *Plant Dis. Rep.* 58(7):660-663, *1974.*
12. Davis, D. D., and Gerhold, H. D., "Selection of Trees for Tolerance of Air Pollutants, Better *Trees for Metropolitan* Landscapes Symposium *Proceedings,* U.S. Forest Service General Technical Report NE-22:61-66, 1976.
13. Davis, D. D., and Wood, F. A., "The Relative Susceptibility of Eighteen Coniferous Species to Ozone, *Phytopathology* 62: 14-19, 1972.
14. Dochinger, L. S., "Effects of Nutrition on the Chlorotic Dwarf Disease of Eastern White Pine, Plant *Dis. Rep.* 48:107-109, 1964.
15. Evans, L. S., Hendrey, G. R., Stensland, G. J., Johnson, D. W., and Francis, A. J., "Acidic Precipitation: Consideration for an Air Quality Standard," *Water Air Soil Pollut.*16:469-509, *1981.*
16. Evans, L. S., Lewin, K. F,, and Cunningham, E. A., "Effects of Simulated Acid Rain on Yields of Field-grown Radishes and Garden Beets, *Am. Chem. Soc.,* Division of Environmental Chemistry, 21 :82-87, 1981.
17. Evans, L. S., Lewin, K. F., and Cunningham, E. A., "Effects of Simulated Acid Rain on Yields of Field-grown Radishes and Garden Beets," *Agriculture* and the *Environment 7* :285-298, *1982.*
18. Evans, L. S., Lewis, K. F., Patti, M. J., and Cunningham, E. A., "Comparison of Experimental Designs To Determine Effects of Acidic Precipitation on Field-grown Soybeans, *' A Specialty Conference on Atmospheric Deposition,* Air Pollution Control Association, SP-49, 1982.
19. Evans, L. S., Gmur, N. F., and DaCosta, F., "Leaf Surface and Histological Perturbations of Leaves of *Phaseolus vulgaris* and *Helianthus annuus* After Exposure to Simulated Acid Rain, " *Am. J. Bet.* 64:903-913, *1977.*
20. Harward, M. E., and Riesenauer, H. M., "Movement and Reactions of Inorganic Soil Sulfur, *Soil Sci.* 101:326-335, 1966.
21. Hayes and Skelly, J. M., "Transport of Ozone From the Northeast United States Into Virginia and Its Effects on Eastern White Pine, *Plant Dis. Rep. 61* :778-782, *1977.*
22. Heagle, A. S., Philbeck, R. B., and Knott, W. M., "Thresholds for Injury, Growth and Yield Loss Caused by Ozone on Field Corn Hybrids, *Phytopathology* 69:21-26, *1979.*
23. Heagle, A. S., Philbeck, R. B., Feicht, P. G., and Ferrell, R. E., "Response of Soybeans to Simulated Acid Rain in the Field, '(J. *Environ. Qual.* (submitted) 1983.
24. Heagle, A. S., Spencer, S., and Letchworth, M. B., "Yield Response of Winter Wheat to Chronic Doses of Ozone, " *Can. J. Bot.* 57: 1999-2005, 1979.
25. Heagle, A. S., and Heck, W. W., "Field Methods To Assess Crop Losses Due to Oxidant Air Pollutants, " *Assessment of Losses Which Constrain Production and Crop Improvement in Agriculture and Forests,* P. S. Teng and S. V. Krupa (eds.), Proceedings of the E. C. Stakman Commemorative Symposium, Misc. Publ. # 7, Agricultural Experiment Station, University of Minnesota, 1980.
26. Heagle, A. S., Heck, W. W., Knott, W. M., Johnston, J. W., Stanel, E. P., and Cowling, E. B., *Responses of Citrus to Acidic Rain From Simulated SRM Fuel Exhaust Mixtures and Exhaust Components,* Internal Report, (Raleigh, N. C.: North Carolina State University, 1978).
27. Heck, W. W., Mudd, J. B., and Miller, P. R., "Plants and Microorganisms, *Ozone and Other Photochemical Oxidants,* (Washington, D. C.: National Academy of Science, 1977).

28. Heck, W. W., Taylor, O. C., Adams, R., Bingham, G., Miller, J., Preston, E., and Weinstein, L., "Assessment of Crop Loss From Ozone, 'J. Air Pollut. Control Assoc. 32:353-361, 1982.
29. Heck, W. W., Larsen, R. I., and Heagle, A. S., "Measuring the Acute Dose-response of Plants to Ozone, Assessment of Losses Which Constrain Production and Crop Improvement in Agriculture and Forests, P. S. Teng and S. V. Krupa (eds.), Proceedings of the E. C. Stakman Commemorative Symposium, Misc. Publ. # 7, (Agricultural Experiment Station, University of Minnesota, 1980).
30 Heggestad, H. E., and Bennett, J. H., "Photochemical Oxidants Potentate Yield Losses in Snap Beans Attributable to Sulfur Dioxide," Science 213:1008-1010, 1981.
31 Hendrey, G. R., Galloway, J. N., Norton, S. A., Schofield, C. L., Burns, D. A., and Schaffer, P. W,, "Sensitivity of the Eastern United States to Acid Precipitation Impacts on Surface Waters, Ecological Impact of Acid Precipitation, D. Drablds and A. Tollan (eds.) (Mysen, Norway: Johs. Grefslie Trykkeri A/S, 1980).
32 Hibben, C. R., "Ozone Toxicity to Sugar Maple, Phytopathology 59: 1424-1428, 1969.
33 Hibben, C. R., "Plant Injury by Oxidant-type Pollutants in the New York City Atmosphere, Plant Dis. Rep. 53:544-548, 1969.
34. Irving, P. M., "Response of Field-grown Soybeans to Acid Precipitation Alone and in Combination With Sulfur Dioxide, ' Ph. D. dissertation, University of Wisconsin, Milwaukee, 1979.
35. Irving, P. M., and Miller, J. E., "Productivity of Field-grown Beans Exposed to A-cid Rain and Sulfur Dioxide Alone and in Combination, "J. Environ. Qual. 10:473-478, 1981.
36, Jacobson, J. S., Troiano, J., Colavito, L. J., Heller, L. 1., and McCune, D. C,, "Polluted Rain and Plant Growth," Polluted Rain, T. Y. Toribara, M. W. Miller, and P. E. Morrow (eds.) (New York: Plenum Publishing Corp., 1980).
37. Jacobson, J. S., "The Influence of Rainfall Composition on the Yield and Quality of Agricultural Crops, Proceedings of the International Conference on Ecological Impact of Acid Precipitation, Sandefjord, Norway, Mar. 11-14, 1980.
38. Jacobson, J. S., and Van Leuken, P., "Effects of Acid Precipitation on Vegetation, Proceedings of the Fourth International Clean Air Congress, Tokyo, 1977.
39. Jensen, K. F., ' 'Response of Nine Forest Tree Species to Chronic Ozone Fumigation, Plant Dis. Rep. 57:914-917, 1973.
40 Jensen, K. F., ' 'Air Pollutants Affect the Relative Growth Rate of Hardwood Seedlings, " U.S. Forest Service Research Paper NE 470 (N. E. Forest Experimental Station, Broomall, Pa., 1981).
41 Johnson, A. H., Siccama, T. G., Wang, D., Turner, R. S., and Barringer, T. H., ' 'Recent Changes in Patterns of Tree Growth Rate in the New Jersey Pinelands: A Possible Effect of Acid Rain, " J. Environ. Qual. 10(4):427-430, 1981.
42. Johnson, A. H., Siccama, T. G., Wang, D., Barringer, T. H., and Turner, R. S., "Decreases in Stream pH and Tree Growth Rates in the New Jersey Pinelands: A Possible Link to Acid Rain, " J. Environ. Qual. 10:427-430, 1981.
43 Johnson, A. H., Siccama, T. G., Turner, R. S., and Lord, D. G., ' 'Assessing the Possibility of a Link Between Acid Precipitation and Decreased Growth Rates of Trees in the Northeastern United States, Proceedings of the American Chemical Society (in press), Las Vegas, Nev.
44. Johnson, D. W., "Acid Rain and Forest Productivity, Proceedings of the International Union of Forestry Research Organizations (IUFRO), Kyoto, Japan, Division I, Ibaraki, Japan, 1981.
45. Johnson, D. W., ' 'The Natural Acidity of Some Unpolluted Waters in Southeastern Alaska and Potential Impacts of Acid Rain, Water Air Soil Pollut. 16:243-252, 1981.
46. Johnson, D. W., and Cole, D. W., "Sulfate Mobility in an Outwash Soil in Western Washington, Water Air Soil Pollut. 7:489-495, 1977.
47. Johnson, D. W., and Cole, D. W., ' 'Anion Mobility in Soils: Relevance to Nutrient Transport From Terrestrial Ecosystems, Environ. Int. 3:79-90, 1980.
48 Johnson, D. W., Cole, D. W., Gessel, S. P., Singer, M. J., and Minden, R. V., "Carbonic Acid Leaching in a Tropical, Temperate, Subalpine and Northern Forest Soil, " Arct. Alp. Res. 9:329-343, 1977.
49. Johnson, D. W., Hornbeck, J. W., Kelly, J. M., Shank, W. T., and Todd, D, E., ' 'Regional Patterns of Soil Sulfate Accumulation: Relevance to Ecosystem Sulfur Budgets, Atmospheric Sulfur Deposition: Environmental Impact and Health Effects, D. S. Shriner, C. R. Richmond, and S. E. Lindberg (eds.) (Ann Arbor, Mich. : Ann Arbor Science, 1980).
50. Karnosky, D. F., ' 'Threshold Levels for Foliar Injury to Populus Tremuloides by Sulfur Dioxide and Ozone, Can. J. For. Res. 6: 166-169, 1976.
51. Kender, W. J., and Spierings, F., "Effects of Sulfur Dioxide, Ozone, and Their Interactions on 'Golden Delicious' Apple Trees, ' Neth. J. Plant Pathol. 81 :149-151, 1975.
52 Klopatek, J. M,, Harris, W. F., and Olson, R. J., "A Regional Ecological Assessment Approach to Atmospheric Deposition: Effects on Soil Systems, " Atmospheric Sulfur Deposition: Environment Impact and Health Effects, D. S. Shriner, C. R. Richmond, and S. E. Lindberg (eds.) (Ann Arbor, Mi.: Ann Arbor Science, 1980).
53 Knight, H. A., and McClure, J. P., "North Carolina's Timber, 1974, " USDA Forest Service Resource Bulletin SE-33 (Southeast Forest Experimental Station, Ashville, N. C., 1975).
54, Kress, L. W., and Skelly, J. M., "Growth Impact of Long Term, Low Concentration Exposure of Several Tree Species to Air Pollution, ' Plant Dis. (in press).
55. Kress, L. W., Skelly, J. M., and Hinkleman, K. H., "Growth Impact of O_3, NO_2, and for SO_2 on Pinus 7'aeda, Env. Monitor. and Assess. (in press), 1982.

56. Larsen, R. I., and Heck, W. W., ''An Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions: Part 3, Vegetation Injury, ' *J. Air Pollut.* Control *Assoc.* 26:325-333, 1976.
57. Lee, J. J., and Neely, G. E., ''CERL-OSU Acid Rain Crop Study Progress Report, " Air Pollution Effects Branch, Corvallis Environmental Research Laboratory, 1980.
58. Matzner, E., and Ulrich, B., ' 'Effect of Acid Precipitation on Soil, *Beyond the Energy Crisis: Opportunity and Challenge,* R. A. Fazzolare and C. B. Smith (eds.) (Oxford, England: Pergamon Press, 1981).
59. McFee, W. W., ' 'Sensitivity of Soils to Acidification by Acid Precipitation, ' *Atmospheric Sulfur Deposition: Environmental Impact and Health Effects,* D. S. Shriner, C. R. Richmond, and S. E. Lindberg (eds.) (Ann Arbor, Mich.: Ann Arbor Science, 1980).
60. McClenahan, J. R., ' 'Community Changes in the Deciduous Forest Exposed to Air Pollution, *Can J. Forest Research* 8:432-438, *1978.*
61. McCormick, L. H., and Steiner, K. C., ' 'Variations in Aluminum Tolerance Among Six Genera of Trees, ' *For. Sci.* 24:565-568, 1978.
62. Miller, Paul R. (cd.), "Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems, USDA Forest Service Technical Report PSW-43, 1980.
63 Miller, P. R., "Oxidant-Induced Community Change in a Mixed Conifer Forest, *Air Pollution Damage to Vegetation,* J. A. Nagegela (cd.), Advances in Chemistry Services 122 (Washington, D. C.: American Chemical Society, 1973).
64 Miller, P. R., and McBride, J. R., "Effects of Air Pollutants on Forests, *Response of Plants to Air Pollution,* J. B. Mudd and T. T. Kozlowski (eds.) (New York: Academic Press, 1975).
65 Miller, P. R., and Elderman, M. J., "Photochemical Oxidant Air Pollution Effects on a Mixed Conifer Ecosystem, " Ecological Research Series, EPA, 600-3-77-104, 1977.
66. Monitor, A. V., and Raynal, D. J., "Acid Precipitation and Ionic Movements in Adirondack Forest Soils, *Soil Sci. Soc. Amer. J. 46: 137-141, 1982.*
67. Norton, S. A., "Sensitivity of Aquatic Systems to Atmospheric Deposition, *Atmospheric Sulfur Deposition: Environmental Impact and Health Effects,* D. S. Shriner, C. R. Richmond, and S. E. Lindberg, (eds.) (Ann Arbor, Mich.: Ann Arbor Science, 1980).
68. Odum, E. P., *Fundamentals of Ecology,* 3d ed. (Philadelphia, Pa.: W. B. Saunders Co., 1971).
69. Olson, R. J., Emerson, C. J., and Nungesser, M. K., ''GEOECOLOGY: A County-level Environmental Data Base for the Coterminous United States" (Oak Ridge, Term.: Oak Ridge National Laboratory, ORNL/TM-7351, 1980).
70. Olson, R. J., Johnson, D. W., and Shriner, D. W., "Regional Assessment of Potential Sensitivity of Soils in the Eastern United States to Acid Precipitation" (Oak Ridge, Term.: Oak Ridge National Laboratory, ORNL/TM-8374, 1982).
71 Pratt, P. F., "AIuminum, *Diagnostic Criteria for Plants and Soils,* H. D. Chapman (cd.) (Abilene, Tex.: Quality Printing Co., Inc., 1965).
72 Puckett, L. J., "Acid Rain, Air Pollution, and Tree Growth in Southeastern New York, *'J. Environ. Qual.* 11:376-381, *1982.*
73 Ragland, J. L., and Coleman, N. T., "Influence of Aluminum on Phosphorus Uptake by Snap Bean Roots, *Soil Sci. Soc. Am. Proc.* 26:88-90, *1959.*
74. Raynal, D. J., Leaf, A., Marion, P. D., and Wang, C. J. K. (eds.), ' 'Effects of Acid Precipitation on a Forest 'Ecosystem' (Syracuse, N. Y.: State University of New York, 1980).
75. Reagan, J. A., EPA, personal communication to OTA, 1983.
76. Reinert, R. A., Shriner, D. S., and Rawlings, J. O., "Responses of Radish to All Combinations of Three Concentrations of Nitrogen Dioxide, Sulfur Dioxide, and Ozone, " *J. Environ. Qual.* 11:52-57, 1982.
77. Research Management Committee (RMC), *The National Crop Loss Assessment Network (NCLAN): 1980 Annual Summer Report* (Corvallis, Oreg. : Corvallis Environmental Research Laboratory, EPA, 1981).
78. Roman, J. R., and Raynal, D. J., "Effects of Acid Precipitation on Vegetation, *Effects of Acid Precipitation on a Forest Ecosystem,* D. J. Raynal, A. L. Leaf, P. D. Marion, and C. J. K. Wang (eds.) (Syracuse, N. Y.: State University of New York, 1980).
79. Rosenquist, 1. Th., *Sur Jord/Surt Vann (Oslo,* Norway: Ingeniorforlaget, 1977).
80. Salathe, L., and Maxwell, D., USDA, personal communication to OTA, 1982.
81. Santamour, F. S., Jr., "Air Pollution Studies on *Platanus* and American Elm Seedlings, *Plant Dis. Rep. 53:482-484, 1969.*
82. Seip, H. M., ' 'Acidification of Freshwater—Sources and Mechanisms, *Ecological Impact of Acid Precipitation,* D. DrabI/s and A. Tollan (eds.) (Mysen, Norway: Johs. Grefslie Trykkeri A/S, 1980).
83, Shriner, D. S., ' 'Effects of Simulated Acidic Rain on Host-parasite Interactions in Plant Diseases, ' *Phytopathology* 68:2 13-218, 1978.
84. Shriner, D. S., "Terrestrial Vegetation-Air Pollutant Interactions: Non-gaseous Pollutants, Wet Deposition, *Air Pollutants and their Effects on Terrestrial Ecosystems,* A. H. Legge and F. V. Krups (eds.), in press (,New York: John Wiley, 1983).
85. Shriner, D. S., ' 'Interactions Between Acidic Precipitation and SO_2 or O_3: Effects on Plant Response, *Phytopathology News* (Abstract) 12: 152, 1978.
86. Shriner, D. S., and Johnston, J. W., ''Effects of Simulated, Acidified Rain on Modulation of Leguminous Plants by *Rhizobium* Spp., " *Environ. Exp. Bet. 21 :199-209, 1981.*
87 Smith, W. H., *Air Pollution and Forests: Interactions Between Air Contaminants and Forest Ecosystems* (.New York: Springer-Verlag, 1980).
88 Smith, W. H., "Air Pollution: A 20th Century Allogenic Influence on Forest Ecosystems, *Effects ofAir Pollutants*

on Mediterranean and Temperate Forest Ecosystems, P. R. Muller (cd.), U.S. Forest Service General Technical Report PSW-43, 1980.

89. Sollins, P., Grier, C. C., McCorison, F. M., Cromack, K., Jr., Fogel, R., and Fredrickson, R. L., "The Internal Element Cycle of an Old-Growth Douglas-Fir Ecosystem in Western Oregon, " *Ecol. Monogr.* 50:261-285, *1980.*
90. Stone, E. H., and Kszystyniak, R., "Conservation of Potassium in the *Pinus Resinosa* Ecosystem, " Science 198:192-193, 1977.
91. Stuanes, A. O., "Release and Loss of Nutrients From a Norwegian Forest Soil Due to Artificial Acid Rain of Varying Acidity, *Ecological Effects of Acid Precipitation,* D. Drablos and A. Tollan (eds.) (Mysen, Norway: Johs. Grefslie Trykkeri A/S, 1980).
92. Tingey, D. T., and Taylor, G. E., Jr., ' 'Variation in Plant Response to Ozone: A Conceptual Model of Physiological Effects, *Proceedings of the 32d University of Nottingham Conference of the School of Agriculture Science Symposium on Effects of Gaseous Air Pollution in Agriculture and Horticulture,* Nottingham, England, Sept. 1-5, 1980.
93. Townsend, A. M., and Dochinger, L. S., "Relationship of Seed Source and Development Stage to the Ozone Tolerance *of Acerrubrum* Seedlings, ' *Atmos. Environ.* 8:956-964, *1974.*
94. Troiano, J., Colavito, L., Heller, L., and McCune, D., ' 'Effect of Simulated Acid Rain and Photochemical Oxidant on Seed Development in Soybean, *Phytopathology 71* :565 (Abstract), 1981.
95. Troiano, J., Colavito, L., Heller, L., McCune, D. C., and Jacobson, J., ' 'Effects of Acidit y of Simulated Rain and Its Joint Action With Ambient Ozone on Measures of Biomass and Yield in Soybean, *Environmental and Experimental Botany 23(2):* 113-119, 1983.
96 Troiano, J., Heller, L. O., and Jacobson, J. S., "Effect of Added Water and Acidity of Simulated Rain on Growth of Field-grown Radish, " *Environ. Pollut. (Se*ries A) 29: 1-11, 1982.
97 Turner, J., Johnson, D. W., and Lambert, M. J., "Sulphur Cycling in a Douglas-Fir Forest and Its Modification by Nitrogen Applications, *Oecol. Plant.* 15:27-35, 1980.
98 Turner, J., Lambert, J. J., and Gessel, S. P., "Use of Foliage Sulphate Concentrations To Predict Response to Area Application by Douglas-Fir, *Can. J. For. Res.* 7:476-480, 1977,
99. Turner, J., Lambert, M. J., and Gessel, S. P., ''Sulphur Requirements of Nitrogen Fertilized Douglas-Fir, *For. Sci.* 25:461-467, 1979.
100. Ulrich, B., ' 'Production and Consumption of Hydrogen Ions in the Ecosphere, *Effects of Acid Precipitation on Terrestrial Ecosystems,* T. C. Hutchinson and M. Havas (eds.) (New York: Plenum Press, 1980).
101. Ulrich, B., Mayer, R., and Khanna, P. K., "Chemical Changes Due to Acid Precipitation in a Loess-Derived Soil in Central Europe, " *Soil Sci.* 130: 193-199, 1980.
102. U.S. Department of Agriculture (USDA), *Agricultural Statistics 1980,* Washington, D. C., 1980.
103. Unsworth, M. H., and Fowler, D., "Field Measurements of Sulfur Dioxide Fluxes to Wheat, *Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, 1974* (Springfield, Va.: National Technical Information Service, CONF-740921, 1976).
104. U.S. Congress, Office of Technology Assessment, Wood *Use: U.S. Competitiveness and Technology,* OTA-ITE-210, August 1983.
105. USDA-Forest Service (USDA), "The Outlook for Timber in the United States, " Forest Resource Report No. 20 (Washington, D. C.: U.S. Government Printing Office, 1973).
106. USDA-Forest Service (USDA), "An Analysis of the Timber Situation in the United States, 1952-2030" (review draft copy) (Washington, D. C.: U.S. Government Printing Office, 0-620-222/3720, 1980).
107. U.S. Environmental Protection Agency, "Effects on Vegetation, *The Acidic Deposition Phenomenon and Its Effects, Critical Assessment Review Papers* (public review draft), 1983.
108 Ward, M. M., "Variation in the Response of Loblolly Pine to Ozone, M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, Va. , 1980.
109, Weaver, J. R., and Clements, F. E., *Plant Ecology,* 2d ed. (New York: McGraw-Hill, 1938).
110, West, D. C., McLaughlin, S. B., and Shugart, H. H., "Simulated Forest Response to Chronic Air Pollution Stress, "J. *Environ. Qual.* 9:43-49, *1980.*
111. Wiklander, L., "The Acidification of Soil by Acid Precipitation, *Grundforbattring* 26:155-164, *1974.*
112. Wiklander, L., "Interaction Between Cations and Anions Influencing Adsorption and Leaching, " *Effects of Acid Precipitation on Terrestrial Ecosystems,* T. C. Hutchinson and M. Havas (eds.) (New York: Plenum Press, 1980).
113. Wilhour, R. G., "The Influence of Ozone on White Ash (*Fraxinus Americana L.),* Ph. D. thesis, Pennsylvania State University, University Park, Pa., 1970.
114. Will, G. M., and Youngberg, C. T., "Sulfur Status of Some Central Oregon Pumice Soils, " *Soil Sci. Soc. Am. J.* 41:132-134, *1978.*
115. Wood, F. A., "The Relative Sensitivity of Sixteen Deciduous Tree Species to Ozone, *Phytopathology 50:579* (Abstract), 1970.
116. Wood, F. A., and Coppolino, J. B., "The Influence of Ozone on Selected Woody Ornamentals, ' *Phytopathology 51:* 133 (Abstract), 1971.
117. Wood, F. A., and Coppolino, J. B., "The Influence of Ozone on Deciduous Forest Tree Species, *Effects ofAir Pollutants on Forest Trees,* VII International Symposium of Forest Fume Damage Experts, 1972.
118. Wood, F. A., and Davis, D, D., "Sensitivity to Ozone Determined for Trees, ' Sci. *Agric.* 17 :4-5, 1969.
119. Wood, T., and Bormann, F. H., "The Effects of an Artificial Acid Mist Upon the Growth of *Betula Alleghaniensis* Britt., *Environ. Pollut.* 7:259-268,1974.
120. Youngberg, C. T., and Dyrness, C. T., ' 'Biological Assay of Pumice Soil Fertility, " *Soil Sci.* 97:391-399, 1966.
121. Yuan, T. L., "Some Relationships Among Hydrogen, Aluminum, and pH in Solution and Soil Systems, *Soil Sci.* 97:391-399, 1963.

B.3 MATERIALS AT RISK

Air pollutants are one of a number of environmental factors—including humidity, temperature fluctuations, sunlight, salts, and micro-organisms—known to cause materials damage. Studies have demonstrated that a broad range of materials, including building stone, rubber, zinc, steel, paint, leather, textiles, paper, and photographic materials are affected by such pollutants as sulfur oxides (SO_x), nitrogen oxides (NO_x), and ozone. For most of the materials under discussion, $S0_x$ (i,e., sulfur dioxide and its transformation products, including sulfates and sulfuric acid) are the chief anthropogenic cause of damage; however, rubber is affected chiefly by ozone, while ozone and NO_x have the greatest effect on textile dyes. Table B-11 summarizes the types of damage that occur to various categories of materials, as well as natural causes of deterioration, methods of measurement, and available mitigation measures.

Pollutants generally damage materials in ways that are not qualitatively different from the weathering effects caused by the natural environment. Consequently, estimating how much of observed damage is contributed by pollution sources is extremely difficult. The diverse pollutant mix characteristic of heavily industrialized urban areas-where greatest amounts of materials damage would be expected—increases the difficulty of pinpointing the cause and mechanisms of damage. In addition, environmental legislation and changes in manufacturing processes have caused pollution patterns to change over time; in particular, concentrations of large particulate have decreased dramatically over the last decade. As a result, pollutant-atmospheric conditions that may have contributed significantly to such notable effects as the deterioration of sculptural stone may no longer prevail in the United States. Finally, the relative contribution of local v. transported pollutants to observed materials damage is unknown. However, since both pollution sources and quantities of sensitive materials tend to be concentrated in urban areas, most researchers consider that local-scale pollutants account for the bulk of currently recognized materials damage.

Two kinds of materials damage are of concern: 1) damage to culturally significant structures and monuments, and 2) damage to reparable or replaceable ‘ ‘common construction material items. The effects of air pollutants on unique or historically important statuary, monuments, buildings, or other artifacts are often irreparable; consequently, their cost to society cannot be described completely in monetary terms. Damages to sculptural stone and bronze, and to historic buildings constructed of such sensitive materials as marble, sandstone, and limestone, are frequently of this nature.

Pollution-induced damages to replaceable materials, and their economic costs, are potentially quantifiable. However, a great deal of information must be taken into account in estimating pollution-related losses. Since those damages tend to be similar in form to other environmental damages to materials, they are likely to affect the rate at which preventive, mitigative, or replacement activities occur, but not to be their sole cause. Little information is available on how pollutant-related damages affect normal maintenance and repair activities. Analysts also need information on the amount of materials damage for which specified pollutant levels are responsible. Most of our knowledge about the rates at which specified pollutant levels cause individual materials to deteriorate is based on field and laboratory experiments using small samples of materials rather than measurements from actual structures. Knowledge about pollutant-material interaction is further limited by the failure of many studies to consider (and measure) important environmental factors. Moreover, estimates of the total quantities of materials exposed and their distribution are limited, so that little information is available to evaluate the extent or the economic consequences of such damage over large geographic areas. Information gaps in each of these areas have, to date, prevented investigators from developing reliable estimates of the overall economic effects of materials damage.

Other factors that may affect how much damage takes place, and about which little is currently known, are: 1) microclimatic variations, 2) the physical placement of materials, and 3) chemical and physical variations in seemingly similar materials. For example, rain may wash sulfate and nitrate particles from exposed surfaces and remove the build-up of soluble pollutant-material residues, while the particles that remain on rain-sheltered surfaces may cause greater damage. Variations in the properties of stone might cause samples from even the same quarry to deteriorate at significantly different rates under similar atmospheric exposure conditions.

Several laboratory and field experiments have estimated ‘ ‘dose-response’ relationships for a limited number of specific pollutant-material interactions. Greatest amounts of data are available on the effects of $S0_x$ on such metals as zinc and *steels* under different weather/atmospheric conditions. Sulfur oxides corrode metals; the volubility of a given metal, and its ability to form stable, protective metal oxide coatings when exposed to the atmosphere, determine its ability to withstand corrosion. Metal corrosion always requires moisture, and tends to accelerate above critical humidity levels that range from 60 to 80 percent, depending on the particular metal.

Table B-II.—Air Pollution Damage to Materials

Materials	Type of impact	Principal air Pollutants	Other environmental factors	Mitigation measures
Metals	Corrosion, tarnishing	Sulfur oxides and other acid gases	Moisture, air, salt, particulate matter	Surface plating or coating, replacement with corrosion-resistant material, removal to controlled environment
Building stone	Surface erosion, soiling, black crust formation	Sulfur oxides and other acid gases	Mechanical erosion, particulate matter, moisture, temperature fluctuations, salt, vibration, CO_2, micro-organisms	Cleaning, impregnation with resins, removal to controlled environment
Ceramics and glass	Surface erosion, surface crust formation	Acid gases, especially fluoride-containing	Moisture	Protective coatings, replacement with more resistant material, removal to controlled atmosphere
Paints and organic coatings	Surface erosion, discoloration, soiling	Sulfur oxides, hydrogen sulfide	Moisture, sunlight, ozone, particulate matter, mechanical erosion, micro-organisms	Repainting, replacement with more resistant material
Paper	Embrittlement, discoloration	Sulfur oxides	Moisture, physical wear, acidic materials introduced in manufacture	Synthetic coatings, storing controlled atmosphere deacidification, encapsulation, impregnation with organic polymers
Photographic materials	Microblemishes	Sulfur oxides	Particulate matter, moisture	Removal to controlled atmosphere
Textiles	Reduced tensile strength, soiling	Sulfur and nitrogen oxides	Particulate matter, moisture, light, physical wear, washing	Replacement, use of substitute materials, impregnation with polymers
Textile dyes	Fading, color change	Nitrogen oxides, ozone	Light, temperature	Replacements, use of substitute materials, removal to controlled environment
Leather	Weakening, powdered surface	Sulfur oxides	Physical wear, residual acids introduced in manufacture	Removal to a controlled atmosphere, consolidated with polymers, or replacement
Rubber	Cracking	Ozone	Sunlight, physical wear	Add antioxidants to formulation, replace with more resistant materials

SOURCE: U.S. Environmental Protection Agency, "The Acidic Deposition Phenomenon and Its Effects," Critical Assessment Review Papers, vol. II, EPA-600/8-83-016B, May 1983.

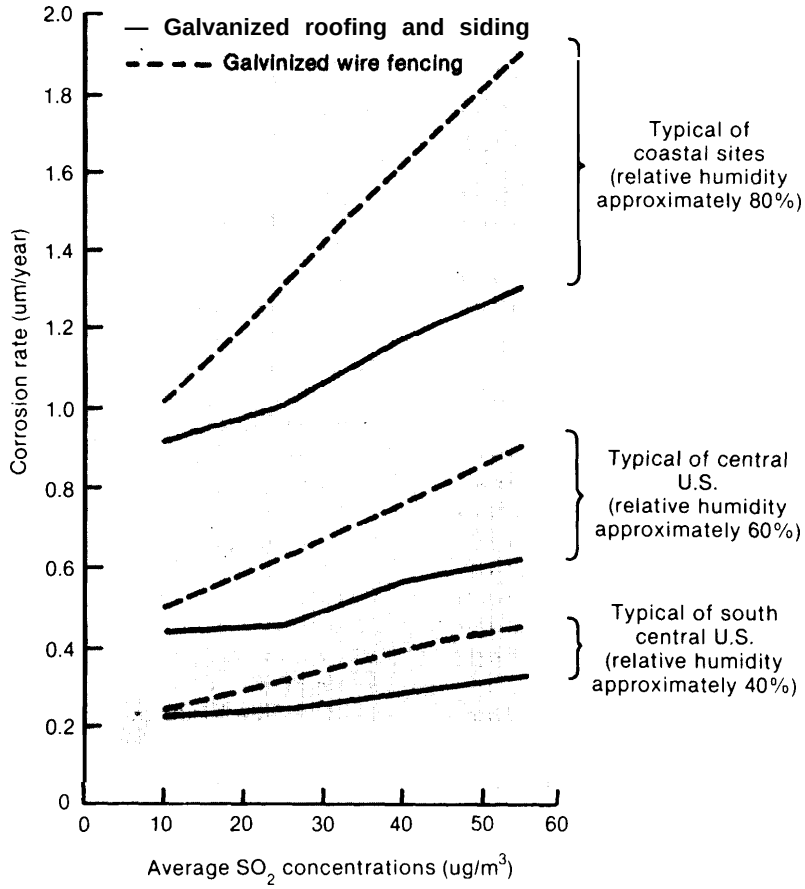
However, results from certain recent studies suggest that the rate of pollutant-induced corrosion depends most on ''time-of-wetness''[1]—i.e., the relative length of time a metal surface is wet (e. g., from morning dew).

Studies have shown that current ambient concentrations of sulfur dioxide (SO_2) can accelerate the corrosion of exposed ferrous metals, and that higher relative humidities significantly increase the extent of SO_2-induced corrosion. However, most uses of ferrous metal products involve the application of such protective coatings as paint and zinc, or the addition of protective alloys. Zinc coatings, used primarily for galvanizing steel, are also corroded by atmospheric SO_2 concentrations, potentially allowing steel underneath to rust, and accelerating maintenance or replacement.

[1]J.E. Yocum and N.S. Baer, "Effects on Materials," *The Acidic Deposition Phenomenon and Its Effects, Critical Assessment Review Papers,* public review draft, U.S. Environmental Protection Agency, 1983

The extent of zinc corrosion at given ambient SO_2 levels depends on such climatic factors as relative humidity, windspeed, and time-of-wetness; and on the surface geometry of the product. The economic importance of zinc has caused its reaction to sulfur pollutants to be extensively studied. A number of researchers have developed dose-response estimates for zinc coatings. For example, figure B-1 4 shows an experimental estimate of the difference between rates of zinc corrosion for large sheets of roofing and siding and those for wire fencing, under different environmental conditions. Rates for galvanized wire and fencing are approximately double those of galvanized sheet exposed to the same environment. The figure suggests that differences between relative humidities in various areas of the country are more significant to corrosion rates than differing SO_2 levels. One researcher has calculated that, for an area with an average humidity of 70 percent, rust could first appear on fencing after 10 years at SO_2 concentrations of 80

Figure B-14.– Estimated Corrosion Rates for Zinc Coatings on Galvanized Steel



SOURCE: Derived from equations in: "Review of the National Ambient Air Quality Standards for Sulfur Oxides: Assessment of Scientific and Technical Information," US. Environmental Protection Agency, 1982.

µg/m (the primary ambient air quality standard), as opposed to an interval of about 30 years required for rust to appear in the absence of SO_2. First rust would occur later on most products, depending on the surface geometries and/or coating thicknesses involved.[2]

A variety of paints has been found to be susceptible to SO_2-induced damage. However, the available evidence suggests that climate tends to play a far more significant part in determining deterioration rates than SO_2 concentrations. Sulfur oxides appear to accelerate normal erosion processes in paint, and to interfere with drying processes of certain paints. Experiments have found that oil-based paints are the most susceptible to damage, probably because they use extenders that react readily with acidic pollutants. No recent studies of the effects of pollutants on paints are available; a limited number of earlier studies were performed during the early 1970's under atmospheric/pollutant conditions that may differ substantially from current ones.

Extensive qualitative information is available on the effects of SO_2 on stone and masonry. In general, the greater the porosity or permeability of stone and masonry, the greater its vulnerability. Such carbonate stones as limestone and marble are particularly sensitive to damage from acidic pollutants. Water serves as a medium for bringing acidifying pollutants into contact with these materials. Crumbling of stone through "normal' deterioration (i. e., through freezing and thawing) may further expose stone surfaces to sulfur pollutants. Sulfur oxides react with calcite, the major constituent of carbonate stone and a cementing material in some sandstones, to form calcium sulfate. Calcium sulfate deposits can form crusts and/or be dissolved by runoff waters, washing away or eroding a layer of stone in the process. Alternatively, calcium sulfate can be transported into the body of the stone or masonry, where it may crystallize and cause the material to crumble or fragment.

In addition, bacteria on the surface of buildings convert atmospheric SO_2 into sulfuric acid for use as a digestive fluid. This fluid can react with the calcium carbonate in limestone, marble, or sandstone to produce calcium sulfate, eroding the building surface when it flakes off or dissolves. The various processes have the same net effect: accelerated stone weathering that causes statues to lose detail and reduces the structural integrity of stone buildings.

A recent study of marble deterioration in the United States has measured decay rates on the order of 2.0 mm/100 years; however, studies of more reactive stones in European cities have yielded substantially greater deterioration rates. Ongoing investigations of 3,900 marble tombstones located in 21 U.S. National Cemeteries are developing data on marble decay in headstones exposed to the environment for 1 to 100 years. Since the marble for these tombstones is supplied from only a few quarries, the effects of climatic and pollutant conditions on a relatively standardized stone can be examined across several regions. Preliminary results show the size of grain in the marble, total amount of precipitation, and local air quality to be significant factors affecting decay.

Efforts to estimate aggregate materials damage to the Eastern United States, whether in physical or economic terms, are hampered by the lack of available information on the distribution of sensitive materials throughout the regions subject to elevated pollution levels. Materials at risk may not be distributed simply as a function of population density; limited field surveys suggest that the period of settlement and urban development, and the local availability of particular materials, also may be influential, For example, a recent field survey of the quantities of paint, galvanized steel, and structural concrete exposed to different concentrations of SO_2 in the greater Boston area suggests that substantially smaller quantities of galvanized steel may be exposed to atmospheric conditions than generally has been assumed. [3] OTA attempts to develop regional materials inventories and/or reliable surrogates for estimation purposes were unsuccessful.

An estimate of U.S. historic resources exposed to elevated ambient concentrations of SO_2 has been prepared under the *United States-Canada Memorandum of Intent on Transboundary Air Pollution.* [4] Using data from the National Register of Historic Places, which includes sites either associated with an event or person, having architectural or engineering significance, or potentially contributing to historic studies, researchers estimated that approximately 16,800 of the 18,300 sites registered as historic places in the 31 Eastern States are in counties that experience average ambient SO_2 concentrations less than 60 µg/m^3. About 900 sites experience SO_2 concentrations ranging from 60 to 80 µg/m^3, and about 600 sites are in counties experiencing concentrations above 80 µg/m^3. Historic places in eight States—Maine, New Hampshire, New York, Pennsylvania, West Virginia, Illinois, Indiana, and Ohio—are exposed to the highest levels of SO_2 concentrations. However, only in two States—New York and Illinois—are more than 20 percent of the registered historic places exposed to annual average SO_2 concentrations above 80 µg/m^3. While such

[2] U S Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Sulfur Oxides: Assessment of.% ientific and Technical Information*, OAQPS Staff Paper, EPA-4501 5-82-007, 1982

[3] TRC Environmental Consultants, *Air Pollution Damage co Man-Made Materials. Physical and Economic Estimates* (Pato Alto, Calif.: Electric Power Research Institute, EPRI EA-2837, 1983).

[4] "Impact Assessment," Work Group 1, *U.S. -Canadian Memorandum of Intent on Transboundary* Air Pollution, January 1983.

a survey can be helpful in indicating an area's relative exposure to potential damages, the ambient SO_2 levels chosen to categorize levels of exposure are arbitrary, representing convenient indicators rather than some known threshold below which materials damage would not take place.

Predicting human responses is perhaps the most significant difficulty in estimating the consequences of pollution-induced materials damage. Individuals confronted with obvious deterioration may choose to ignore it, accelerate cleaning, painting, or replacement, or substitute a less susceptible material. Unless the damage causes some change in the material's utilization or results in some cost to owners, it will have no measurable economic significance. For example, metal guardrails on highways are likely to suffer damage from air pollutants; however, highway accidents generally restrict a guardrails useful life to a greater extent than does air pollution. Ozone causes rubber and other elastomers to lose elasticity prematurely, and become brittle. Consequently, automobile tires and other exposed products are routinely manufactured with antioxidant agents—the cost of these additives, rather than a shortening of usable life, represents this economic effect of air pollution.

Since the early 1970's, a number of studies have calculated annual costs of materials damage due to air pollutants by estimating *amounts of damage* and deriving some monetary equivalent for these damages. While the availability of dose-response relationships for certain pollutant-material interactions permit this type of analysis, the uncertainties involved are quite large. Moreover, such studies still must rely on broad hypotheses about material exposure and individual economic behavior.

For example, a recent study estimated the amount by which materials damage would be reduced if European OECD member countries decreased SO_x emissions by about 20 percent and 50 percent from projected emissions of about 24 million tons in 1985.[5] Estimates were made only for corrosion to zinc and galvanized steel, and for damage to paint coatings. The study assumed that each of these materials was used in proportion to the population, using OECD annual statistics on the use of paint and of zinc for galvanizing in member countries. Galvanized materials were assumed to be unpainted initially; sheet and products manufactured from sheet were assumed to be painted, and wire replaced, after some corrosion occurred. Repainting was assumed to occur at the economically optimal time; however, materials older than 25 years were excluded, and no consideration was given to withdrawal of materials prior to that time. These assumptions yielded an estimate that costs of damage would be reduced by $450 million annually (1979 dollars) if emissions were reduced by about 20 percent, and by $960 million annually if emissions were reduced by about 50 percent, by 1985.

A recent study commissioned by EPA's Office of Air Quality Planning and Standards used macroeconomic and statistical techniques—rather than physical dose-response approaches—to estimate pollution-related economic losses from materials damage.[6] The method statistically estimates how much of the observed variations in expenditures for goods and services sensitive to differing air pollution levels is due to a variety of economic and climatological factors, and how much of the remaining variation can be attributed to differing SO_2 levels. This methodology has the advantage of taking into account a wider variety of potential responses to pollution-related damages (e. g., relocating, substituting pollution-resistant materials, doing nothing) than studies assuming that all perceived damages would be remedied by repair or replacement. The study has the further advantage of taking into account costs due to air pollution, but not perceived as such—e.g., accelerated depreciation of machinery. However, such statistical methods can show only that a **correlation** exists between pollution and the materials-related costs, and cannot prove that pollution causes the economic effect.

The EPA-sponsored study calculated the value of reducing SO_2 levels nationwide from the primary NAAQS (365 $\mu g/m^3$, 24-hour averaging time) to a hypothetical secondary standard of 260 $\mu g/m^3$ (24-hour averaging time). * Calculations of benefits were made for households in 24 standard metropolitan statistical areas for electric utility maintenance; for agriculture; and for six selected industries for which adequate economic data were available— 1) meat products, 2) dairy products, 3) paperboard containers and boxes, 4) fabricated structural metal products, 5) metal forging and stampings, and 6) metalworking machinery. * * Results were then

[5] Organization for Economic Cooperation and Development (OECD), *The Costs and Benefits of Sulphur Oxide Control A Methodological Study* (Paris OECD, 1981).

[6] E. H. Manuel, Jr., et al., "Benefits Analysis of Alternate Secondary National Ambient Air Quality Standards for Sulfur Dioxide and Total Suspended Particulate, produced by Mathtech, Inc., under contract to U.S Environmental Protection Agency, OAQPS, Research Triangle Park, N .C., 1982

*The current secondary standard—1 ,300 $\mu g/m^3$, 3-hour averaging time—was found to be less restrictive, for most locations, than the primary standard. Using statistical averaging techniques to match 3-hour to 24-hour standards, only 5 counties in the country (out of 182 counties for which air quality data were available) would require additional controls to meet the secondary standard, as compared to the primary standard.

● *These industries correspond to Standard Industrial Classification (SIC) codes 201, 202, 265, 344, 346, and 354.

extrapolated to households throughout the United States, comparable manufacturing sectors, and electric utility operation and maintenance. The study concluded that reducing SO_2 emissions in urban areas to meet the 260 µg/m^3 standard would create benefits of approximately $300 million annually for about half of the households and 7 to 9 percent of the producing sector* in the United States. These results cannot be extrapolated to provide estimates of benefits to the Nation overall; the lack of necessary data precludes analyzing the remainder of the Nation's economy in this manner.

*The study defines the ' 'producing sector' to include agriculture, forestry, and fisheries; mining and construct ion, manufacturing; transportation, communication, and utilities; commercial and services, government; and other

B.4 VISIBILITY IMPAIRMENT*

Introduction

An observer's perception of "visibility" integrates several factors—general atmospheric clarity or haziness, the total distance over which objects can be seen, their apparent color and contrast with the sky, and discerned details of line, texture, and form. Visibility degradation is one of the most obvious effects of air pollution. The present Clean Air Act (CAA) addresses the impairment of visual range in pristine areas, atmospheric discoloration, and the presence of actual smoke plumes (''plume blight' '). The reduction in visibility from many and diverse sources spreading over a large area-regional haze —has not yet been addressed. Regional haze reduces visibility in all directions from an observer, is relatively homogeneous, and can occur on a geographic scale ranging from a city to a multi-State region. Haze conditions can reduce contrast, cause distant objects to disappear, and nearby objects to appear discolored and ' 'flattened, add brown or grey discoloration to the atmosphere, and decrease the number of stars visible in the night sky.

Visibility impairment is of concern both for esthetic reasons (especially in areas of great natural beauty) and practical concerns (transportation operations). Limited studies suggest that actual measurements of visibility correlate with: 1) perceived air quality, and 2) perceived property values in Los Angeles and the rural Southwest. Preliminary attempts to quantify visitors' "willingness-to-pay' to preserve scenic vistas have been quite variable. The major effects of visibility on transportation are related to air traffic. Available data show that episodic regional haze over large segments of the East tends to curtail some segments of general aviation aircraft and slow commercial, military, and other instrument flight operations on the order of 2 to 12 percent of the time during the summer. The Federal Aviation Administration (FAA) restricts visual flight operations when visibility falls below 3 miles. Table B-12 summarizes efforts to characterize the social, economic, and psychological value of various levels of visibility.

A variety of natural and anthropogenically produced particles are capable of interfering with the passage of light and contributing to regional haze. Liquid or solid particles* * ranging from 0.005 micrometer (pm) to coarse dusts on the order of 100 µm can either scatter or absorb light, reducing visibility through the extinction of light. Theoretical and empirical results provide strong evidence that visibility reduction caused by urban and regional haze normally is controlled by **fine particles,** primarily sulfates (smaller than 2.5 µm in diameter). The only important situations in which large particles dominate are such naturally occurring phenomena as precipitation, fog, and dust storms, or manmade phenomena like construction, agricultural and forest slash-burning, and open-pit mining.

Factors Affecting Visibility

Natural

Natural causes of impaired visibility include dust, fog, low clouds, precipitation, elevated humidity, seaspray, volcanic emissions, and forest fires. Humidity is a particularly significant visibility determinant, as it not only reduces visibility levels in itself, but also affects the visibility-reducing properties of other airborne materials. At high humidity levels, fine airborne particles take up

● This appendix is based primarily on the OTA background paper "Review of the Long-Range Transport of Sulfate Contribution to Visibility Impairment, by Brand L Niemann, 1983.

" ● Nitrogen dioxide is the only gaseous pollutant in the atmosphere capable of contributing to the extinction of light; however, its concentrations are rarely large enough to result in a substantial contribution.

Table B-12.—Summary of Qualitative Evidence for Visibility-Related Values

Effect of increased visibility	Affected groups	Averaging times[a]	Supporting observation
Transportation:			
More efficient, lower risk operations, visual approach permitted	Airport users, operators civilian and military	1-3 hr. readings	Visual approaches permitted when visibility >3-5 miles; airport specific (FAA, 1980b)
Increased opportunity to operate aircraft	General aviation aircraft (noninstrument capable pilots, aircraft)	1-3 hr. readings	VFR permitted when visibility >3 miles (FAA, 1980a)
Aesthetic:			
1) *Social criteria:*			
Decreased perception of air pollution	Substantial percentage of general population; urban areas	Daily to annual	Perception of air pollution in Los Angeles significantly related to visibility for all averaging times (Flachbert and Phillips, 1980). Perception, annoyance significantly related to particulate matter (Schusky, 1966)
Options values; maintaining or increasing opportunity to visit less impaired natural and urban settings	Outdoor recreationists, campers, tourists	Daily, peak visitation in summer months	Aggregate of activity values in iterative bidding studies suggests importance of options values (Rowe and Chestnut, 1981)
Improved view of night sky	Amateur astronomers, other star watchers	Nightly	Decrease in star brightness by fine particles (Leonard, et al., 1977)
2) *Economic criteria:*			
Increased property values	Home owners	Long term	Property values related to perception of air pollution, hence visibility (Rowe and Chestnut, 1981; Brookshire, et al., 1979)
Enhanced enjoyment (user or activity values) of environment in:			
a) Urban settings	Urban dwellers	Long term	Willingness to pay for increased visibility in urban (Brookshire, et al., 1979) and nonurban settings (Rowe, et al., 1980)
b) Natural settings	Outdoor recreationists, campers, residents of nonurban areas	Daily, peak visitation in summer months	
3) *Psychological criteria:*			
Existence values; maintaining pristine environments	General population	Long term	Existence values may far outweigh activity or user values (Rowe and Chestnut, 1981)
Less concern over perceived health effects	General population, urban areas	Daily to long term	About two-thirds of bid for improved visibility in Los Angeles was related to concern over potential health effects (Brookshire, et al., 1979)

aRepresents EPA staff judgment of most important averaging time based on supporting observatlon Because averaging times are related it IS difficult to specify single (long or short) averaging time as most significant, Perception of visibility IS essentially instantaneous.

SOURCE: U.S. Environmental Protection Agency, "Review of the National Ambient Air Quality Standards for Particulate Matter," EPA-45015-82-001, January 1982

water directly from the atmosphere; this can cause fine-particle scattering to increase by a factor of 2 as relative humidity increases from 70 to 90 percent. The annual mean relative humidity is greater than 70 percent east of the Mississippi, and greater than 80 percent in Maine and several Atlantic coastal areas. Dense fog is, of course, most frequent in coastal and mountainous areas, with the northern Appalachian mountains, northern California coast, and Nantucket Island showing 50 to 80 days/year of dense fog. Blowing dust is a significant cause of visibility impairment only in the southern Great Plains and Western desert regions.

On a regional or national basis, the frequency of relevant meteorological phenomena has been determined by the National Oceanic and Atmospheric Administration (NOAA) and individual researchers. However, reports from **individual** sites usually have not included information on the occurrence of these natural phenomena during impaired visibility. Without such information, it is difficult to evaluate how much of observed visibility degradation is due to natural causes.

Manmade

Anthropogenic particles contributing to reduced visibility originate from stationary and mobile sources and may be emitted directly or formed in the atmosphere through transformation of such gaseous pollutants as $S0_2$. The origin and composition of fine particles (less than 2.5 pm) is generally different than that of large or coarse particles. Fine particles tend to originate from the condensation of materials produced during combustion (e. g., lead) or atmospheric transformation of gases (e.g., sulfates). (See app. C, "Atmospheric Chemistry. Atmospherically formed fine particles—particularly sulfates—can circulate in moving air masses, and subsequently be dispersed over large geographic areas far from source regions. Since larger particles settle out most rapidly, elevated levels of coarse particles usually occur only near strong emissions sources.

Evidence for Anthropogenically Caused Decrease in Visibility

Both current and historical data bases can provide insight into the relationship between manmade air pollution and visibility degradation.

Current information on amounts and location of $S0_2$ and NO_x emissions can be related to the monitoring data for air concentrations and deposition of sulfates and nitrates. In conjunction with meteorological data and visibility measurements, this information allows detailed analysis of factors contributing to short-term (e. g., seasonal) changes in visibility.

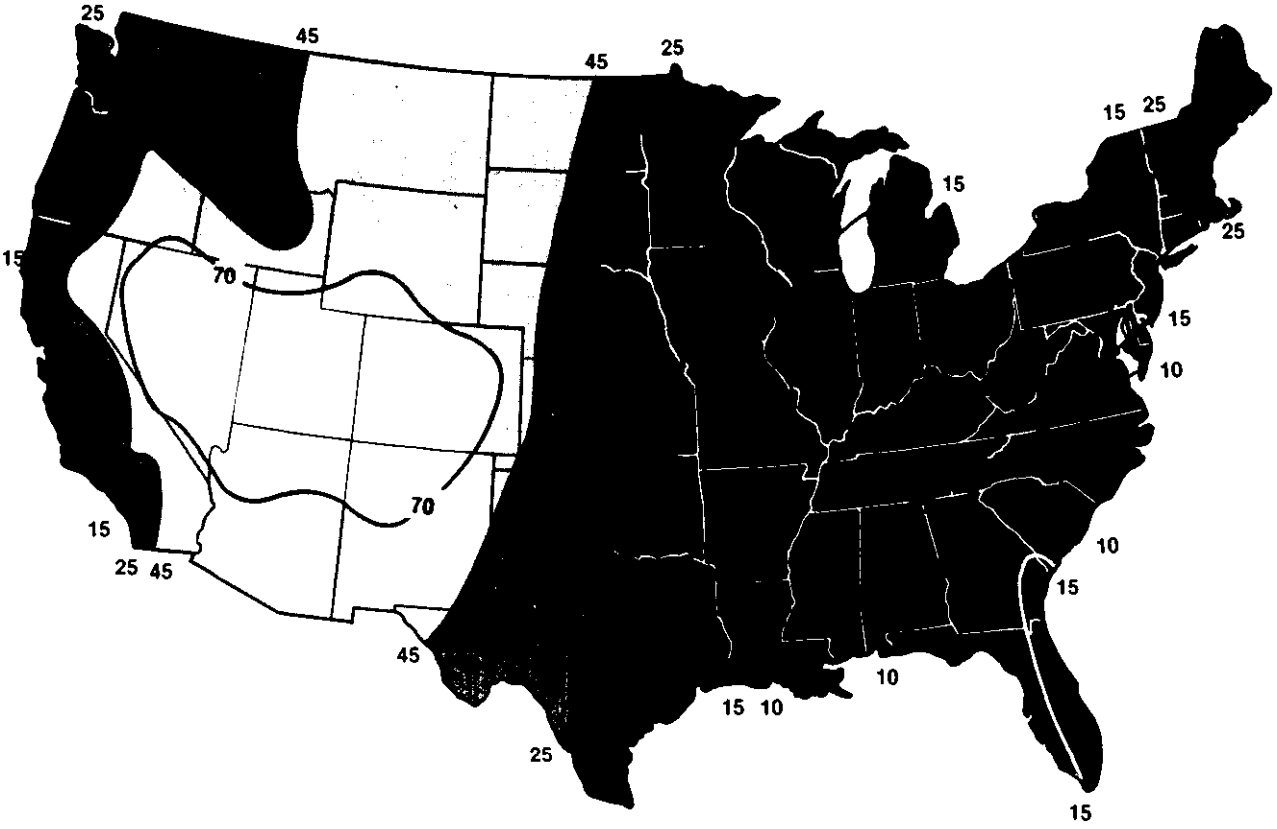
Historical visibility data can be used to infer long-term trends in air quality, because changing patterns of visibility reflect variation in natural and anthropogenic emissions and meteorology over the long term.

General Conclusions

Based on: 1) current assessments of natural sulfur sources and regional fine-particle levels, 2) long-term historical visibility data in the Northeast from 1889 to 1950, and 3) examination of airport visibility trends after deleting data potentially influenced by natural sources (fog, precipitation, blowing dust), anthropogenic sulfate levels appear to be the dominant component of Eastern regional haze. Investigations over the past decade, using a variety of data bases, show several areas of agreement:

- Examination of airport data, pollution 'measurements, and satellite photography indicates that region-scale hazy air masses move across the Eastern United States and cause significant visibility reduction in areas with little or no air pollutant emissions. In addition, aircraft measurement of the plumes of large powerplants, smelters, and major urban areas have tracked the visibility impairment by sources for 30 to 125 miles downwind.
- Light scattering by anthropogenic particulate pollution—of which fine sulfate particles are the most important—appears to be the predominant cause of Eastern regional haze. Recent studies indicate that sulfate in the Eastern United States is responsible for about 70 percent of visibility impairment in the summer, and 50 percent on an annual basis. Nitrates rarely contribute substantially to visibility degradation in the East, while carbon particles appear more important within urban areas than in suburban or rural areas.
- Contributions to visibility degradation in the West appear to be more varied. Depending on the site analyzed, substantial contributions have been shown for nitrates, carbon, sulfates, and dust. Analyses of the relationship between copper-smelter emissions and regional visibility degradation in the Southwest, however, have shown correlations between $S0_2$ emission levels and the percent of time during which reduced visibility occurs.
- Currently highest average visual ranges for the United States occur in the mountainous Southwest (annual visibility generally greater than 70 miles). Annual median risibilities east of the Mississippi and south of the Great Lakes are less than 15 miles, with the Ohio River Valley showing the lowest visibility range (fig. B-15). While some of this difference stems from lower relative humidity levels in the West, a more important factor is the higher regional fine-particulate loadings in the East (e. g.,

Figure B-15.— Median Yearly Visual Range (miles) for Suburban and Nonurban Areas



Data from 1974-76 estimated from visual observations and other methods

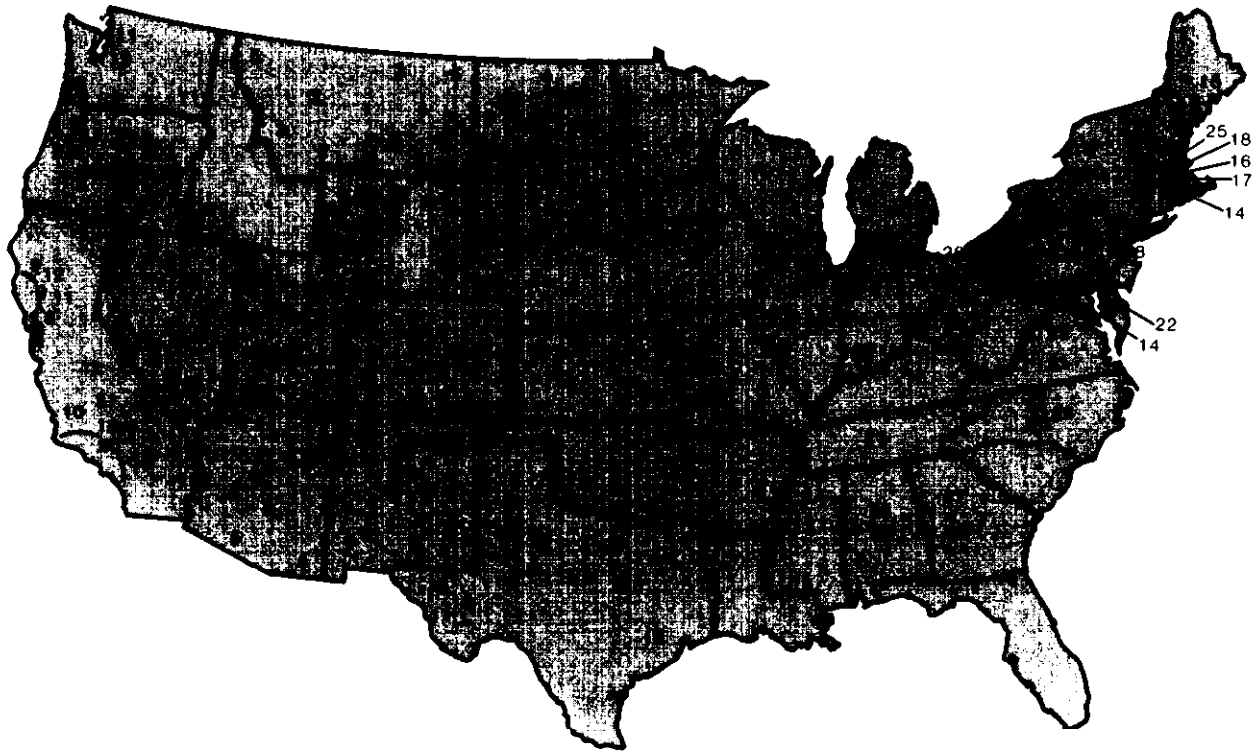
SOURCE: J. Trijonis and R. Shapland, 1979: Existing *Visibility Levels in the U. S.. Isopleth Maps of Visibility in Suburban/Nonurban Areas During 1974-76,* EPA 450/5-79-010, U.S. Environmental Protection Agency, Research Triangle Park, N.C.

about 25 µg/m^3 in the summer) than in the West (about 4 µg/m^3 in the summer). (See fig. B-16.)

- National visibility maps show that summertime visibility is much lower than annual-average visibility levels in the East, and that the largest regional gradients in visibility are found in California. In California, the two major pockets of impaired visibility (Los Angeles Basin and southern San Joaquin Valley) are due more to local- or medium-range transport than to long-range transport, while in the East, the major area of impaired visibility (Ohio River Valley) is undoubtedly related to the high density of SO_2 emissions. The cause of pockets of impaired visibility found in the Gulf and mid-Atlantic coasts is less apparent, but probably reflects a combination of natural and anthropogenic factors.
- Trend analyses of visibility at Eastern airports for the period of 1950-80 indicate that while wintertime risibilities improved in some Northeastern locations, overall regional visibility declined until 1974, then slightly improved. However, summertime, often the best season for visibility in the 1950's, is currently marked by the worst episodic regional haze conditions. * (See fig. B- 17.)
- From the early 1960's through the mid-1970's, U.S. control programs resulted in substantial reductions in total suspended particles (TSP) and $S0_2$ levels in most of the more polluted urban areas. However, during this same period, available information suggests that Eastern U.S. regional concentrations of summertime fine particles, particularly sulfates, increased.

● While quantities of smaller particles (less than O 1 µm) are sometimes present in polluted air masses, they are relatively ineffective at scattering light; larger particles are effective light-scatterers, but are rarely present in sufficient concentrations to affect visibility substantially

Figure B-16.—Airborne Fine-Particulate Concentrations (μg/m³) (summer 1977-81)



SOURCE: Composite map based on data from 3 networks: EPA's Inhalable Particulate Network, EPA's Western Fine Particle Data Base, and EPRI SURE network.

Mechanisms of Visibility Degradation

In a completely "pure" atmosphere, visual ranges across the horizon can extend up to 200 miles; such conditions are occasionally approached on clear days in the Southwestern United States. The extent of visibility degradation is determined both by the size and concentration of particles in the atmosphere. For example, adding 10 μg/m³ of coarse particles-greater than 2.5 μm in diameter—to clean air would reduce visibility moderately, from 130 km to about 108 km. If, however, the particles were very small (in the optically critical size range of O. 1 to 1.0 pm), the addition of 10 μg/m³ would reduce visibility significantly, from 130 km to about 44 km. (Table B-13 shows how the relative contribution of fine and coarse particles varies from location to location.)

Adding even low concentrations of substances to pristine environments has a profound effect on visibility. The addition of 1 μg/m³ of fine particles to a clean atmosphere can reduce visual ranges by about 30 percent. As the atmosphere is degraded, each additional increment of particulate matter has a smaller effect on visibility-adding 1 μg/m³ of fine particles to an atmosphere with a 20-mile visual range reduces visibility by only 3 percent (see fig. B-18).

Two fine-particle components, hydroscopic (water-absorbing) sulfates and elemental carbon, generally tend to be most important in reducing visibility. In the East, sulfate compounds are the predominant component in the fine particles causing light scattering over wide regions, while elemental carbon accounts for most light absorption in urban areas.

Fine particles between 0.1 and 2.0 μm diameter are the most efficient at scattering light, and appear to account for the bulk of visibility degradation due to light scattering. * Sulfates and nitrates, the transformation products of $S0_2$ and NO_x, exist in the atmosphere primarily as particles ranging from 0.1 to 1.0pm in size before being deposited to the earth in wet or dry form.

● **Recent evidence suggests that at least some of the difference may be due to shorter and less frequent episodes of elevated humidity during the 1950's than occurred in the 1970's, C, Sloane, "Summertime Visibility Declines: Meteorological Influences, "** *Atmospheric Environment* 17(4):763-74, *1983*

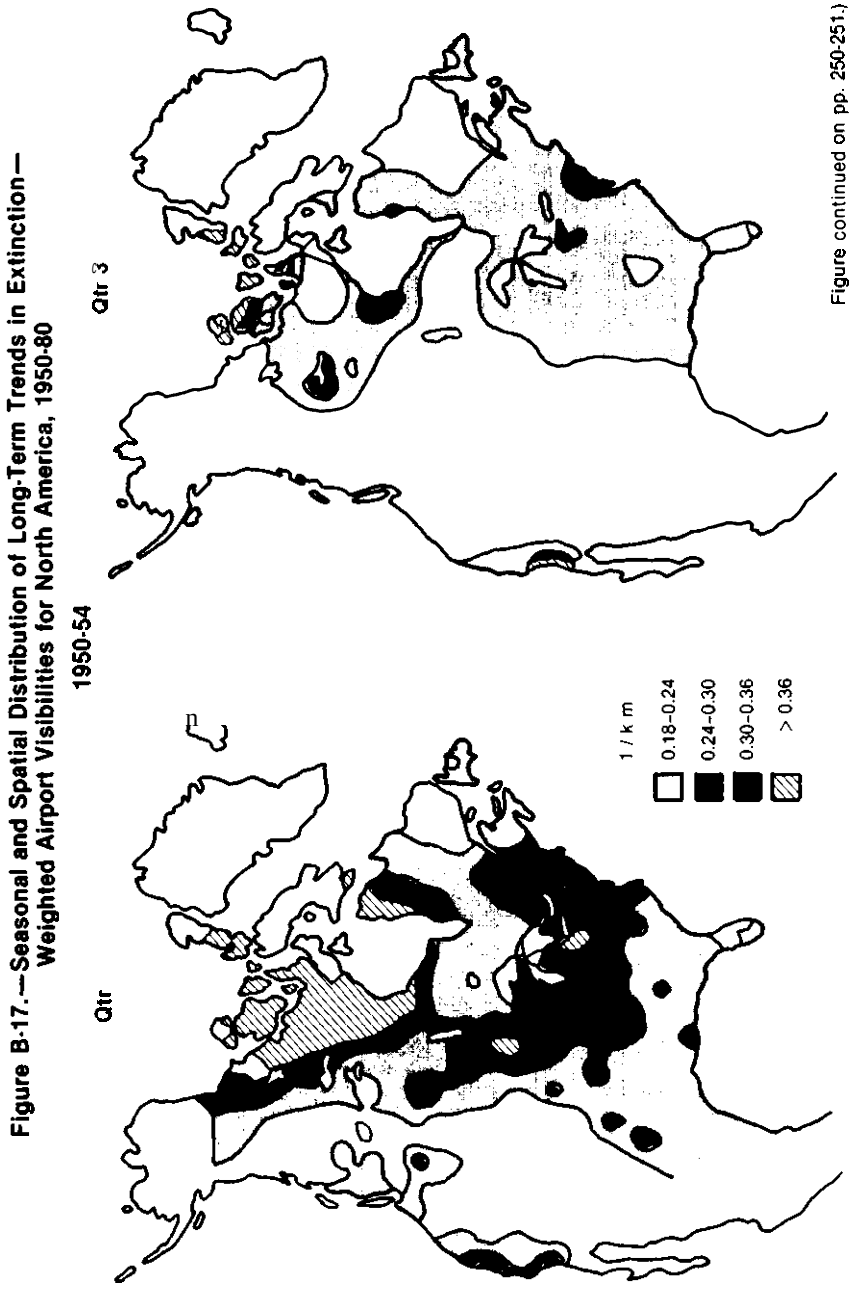


Figure B-17.—Seasonal and Spatial Distribution of Long-Term Trends in Extinction—Weighted Airport Visibilities for North America, 1950-80

Figure continued on pp. 250-251.)

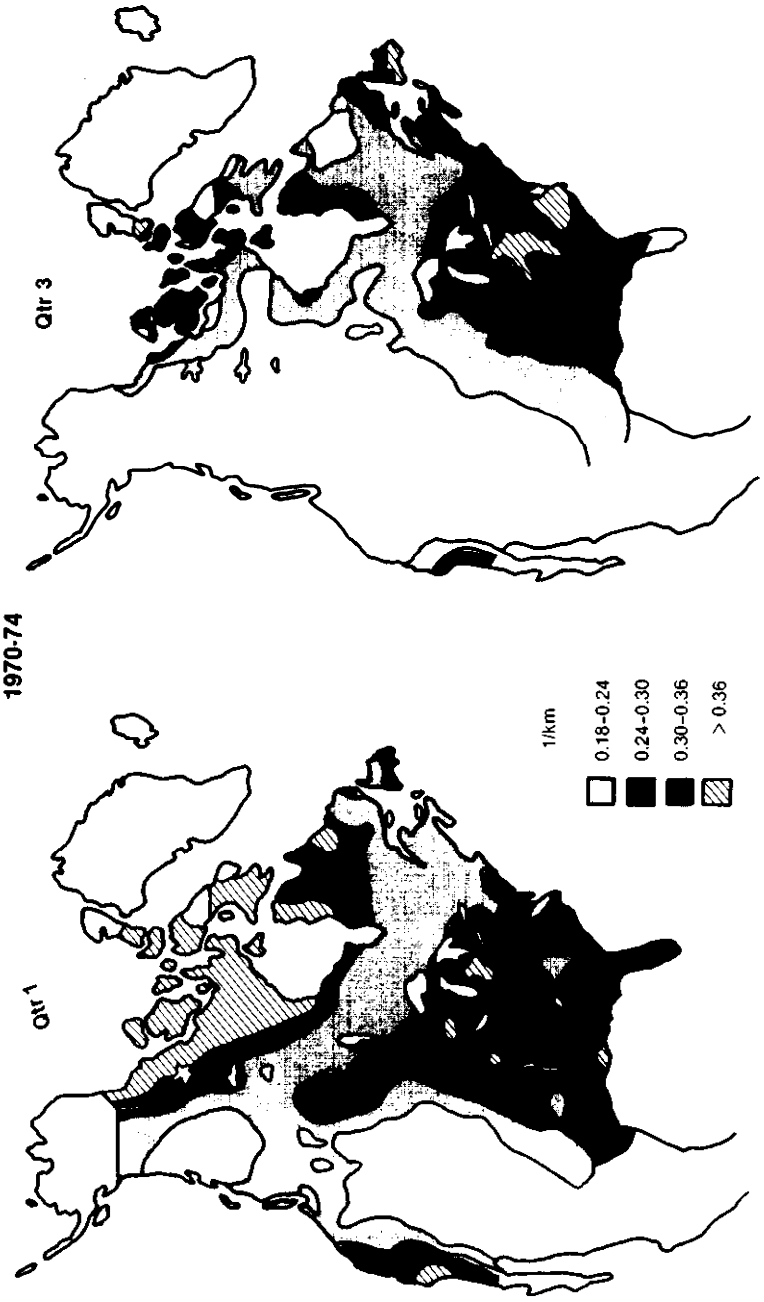
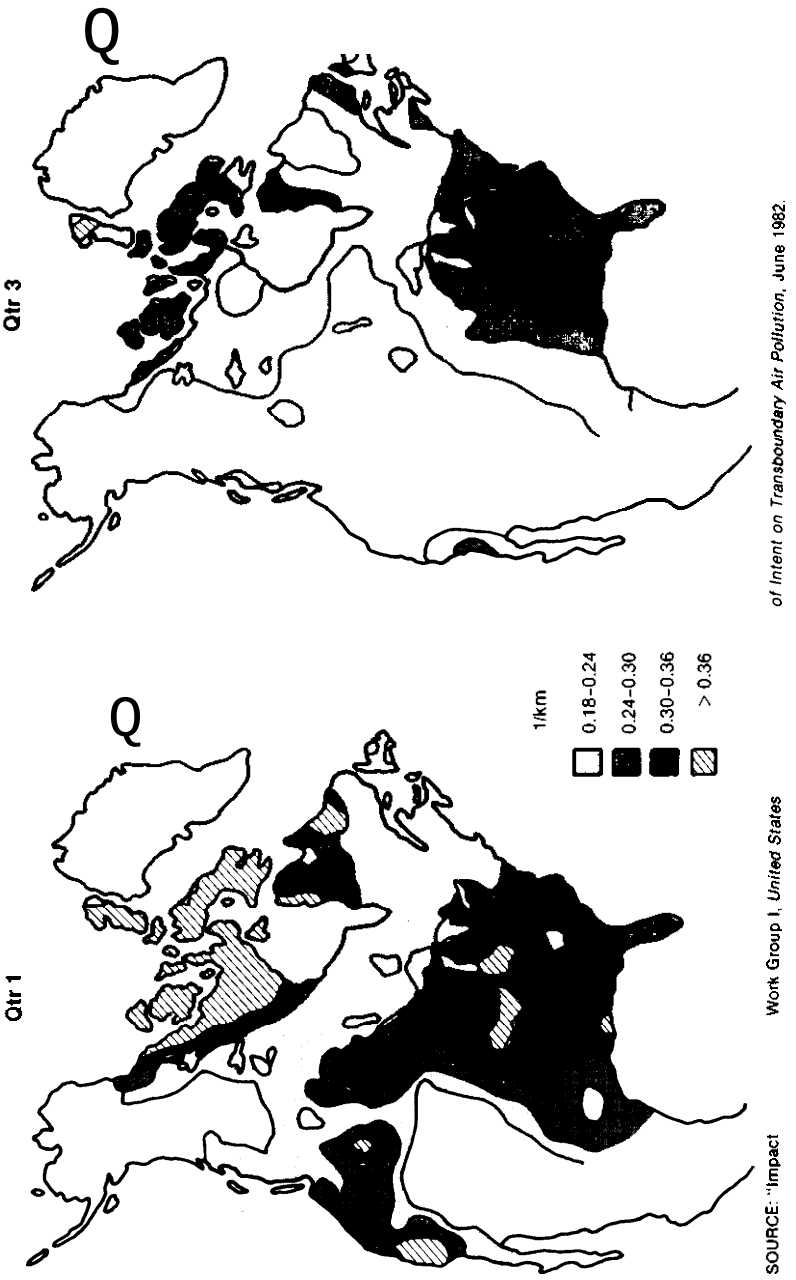


Figure B-17.—Seasonal and Spatial Distribution of Long-Term Trends in Extinction—Weighted Airport Visibilities for North America, 1950-80—Continued

1970-74

Figure B-17.—Seasonal and Spatial Distribution of Long-Term Trends in Extinction—Weighted Airport Visibilities for North America, 1950-80—Continued



SOURCE: "Impact Work Group I, *United States of Intent on Transboundary Air Pollution*, June 1982.

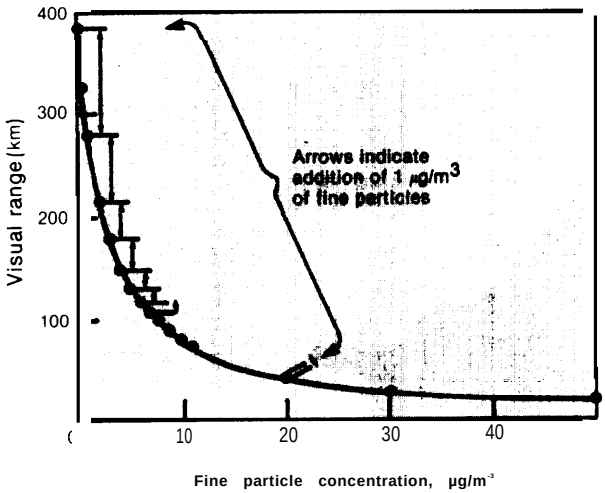
Table B-13.—Characterization of Airborne Particulate. Matter Concentrations, 1977.81[a]

Long-term (6-12 months) average	TSP[b]	FP[c] (<2.5 µm)
Eastern locations:		
Undisturbed	30-40	15-20
Downtown	60-90	20-30
Industrial	60-110	25-45
Add Western locations:		
Undisturbed	15-20	3-5
Downtown	...75-130	15-25
West coast:		
Los Angeles area.	90-180	30-40
Pacific Northwest	45-95	15-25

aThe data used from the three networks include: EPA's Inhalable Particulate Network, 35 urban sites, April 1980-March 1981; EPA's Western Fine Particle Data Based, 40 nonurban sites, Summer 1980-Spring 1981; Electric Power Research Institute SURE data base, 9 rural sites, 15 months, 1977-1978.
bTotal Suspended Particulates.
cFine particulate

SOURCE: Pace, T. G. (1981). Characterization of Particulate Matter Concentrations. Memorandum to John Bachmann, Strategies and Air Standards Division, Office of Air Quality Planning and Standards (Dec. 30, 1981).

Figure B.18.—The Effect of Fine Particles on Visual Range

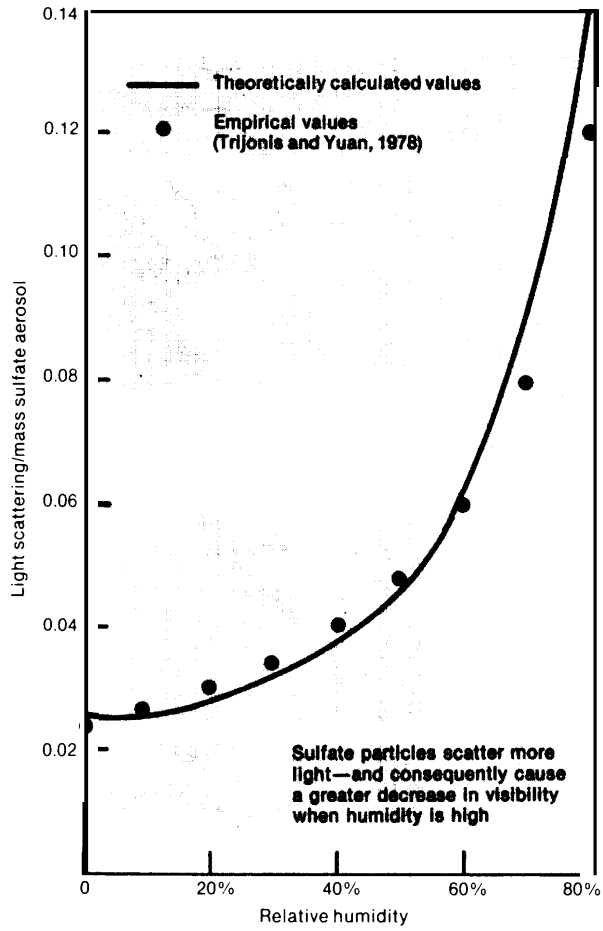


In clean areas (where visual range is greater than 200 km), adding small quantities of fine particles to the atmosphere degrades visibility markedly; the same increment added to an area with low visibility has little effect.

SOURCE: U.S. Environmental Protection Agency, *Protecting Visibity, An EPA Report to Congress, 1979.*

The strong light-scattering properties of sulfate and nitrate particles are due to their affinity for water vapor; moreover, the greater the relative humidity of the atmosphere, the greater the capacity of sulfate particles to scatter light, especially when relative humidities rise above 70 percent (see fig. B-19).

Figure B-19.—The Relationship Between Relative Humidity and Light Scattering by Aerosol Sulfate



SOURCE: U.S. Environmental Protection Agency, *Protecting Visibility, An EPA Report to Congress,* 1979.

Carbon particles appear to be the major pollutant involved in absorbing light. In urban settings, where concentrations of carbon particles tend to be relatively high, light absorption can be as important a factor in visibility degradation as light scattering; however, on a regional scale, particularly in rural settings, particle scattering accounts for upwards of 75 percent of light **extinction**—the standard measure of visibility degradation.

Measurement Techniques

The physics and chemistry of light scattering and absorption is well understood. A variety of techniques is available to measure scattering and absorption with reasonable accuracy. The simplest of these involves estimation of visual range, using objects at specified distances from an observer as reference points for estimating the distance beyond which distinct visual

phenomena cannot be observed. Such estimates are inherently imprecise, and can be affected by such subjective factors as the observer's visual acuity. * However, the availability of such observations for a wide variety of sites over a multiyear period—visual ranges have been recorded on a daily basis at hundreds of U. S. and Canadian airport sites in urban, suburban, and rural locations since 1948—makes this data base indispensable for performing time-trend analyses of visibility. Comparisons of historical patterns for visibility in the Eastern United States such as those in figure B-17 necessarily derive from such data.

Telephotometry provides statistical measurements analogous to perceived visual ranges, while affording greater precision. The technique involves the use of a telescope capable of measuring the contrast between the brightness of a faraway object and the horizon sky surrounding it. In addition, direct measurements of the portion of a light source lost to atmospheric interference are made with such devices as sun photometers, instruments to measure direct solar radiation intensity, and integrating nephelometers. This last device passes a light source through a given air sample to determine how much light scattering occurs. While nephelometers are not capable of measuring light absorption, and may distort measurements as a consequence of air sample manipulation, they are currently a widely used method of measuring visibility, and are the primary means available for determining how individual pollutants or pollutant mixes affect visibility. The nephelometer has been the basis for most of the experimental data relating cause and effect in visibility degradation studies.

No single measurement technique is adequate at present for assessing all significant factors involved in visibility impairment. The most productive areas of recent research have involved comparing two or more of the available monitoring techniques at selected sites or in new networks where fine particulate and meteorological measurements are made concurrently.

Until recently, visual-range/pollutant-concentration studies dominated the visibility literature; a number of studies completed over the past few years, however, have relied on nephelometer and related measurements to determine correlations with pollutant levels. Imprecision may be introduced into either of these analytical techniques by discrepancies between pollution- and visibility-monitoring locations, as well as by limitations in measurement techniques mentioned above. However, a large group of studies have found consistent patterns pointing to sulfates as the major cause of regional-scale visibility degradation.

"Prior to 1970, observations beyond 15 miles were not reported at most stations in the Midwestern States The coarseness of distant observations increases with distance due to fewer available targets Visibilities greater than 15 males are now estimated in multiples of 5 miles

Key Studies

A description of some of the key studies will illustrate three different ways researchers have used incomplete data to examine the visibility/sulfate relationship:

- the integrated use of multiple data bases,
- specific case studies, and
- modeling efforts.

Use of Multiple Data Bases: "Capita"

The most extensive analyses of spatial and temporal patterns of visibility impairment in the Eastern United States have been performed by the Center for Air Pollution Impact and Trend Analysis (CAPITA).[7] The CAPITA analyses have used four historical data bases: airport visual range at 147 U.S. and 177 Canadian sites from 1948 to 1980; Blue Hill Observatory visual-range data (3 mountaintops—32, 72, and 107 km from the observatory) for 1889 to 1959; the NOAA/WMO** turbidity network of 25 to 35 sites during 1960 to 1975; and direct solar radiation intensity measurements at Madison, Wis., from 1920 to 1978. Significant findings of the trend analysis were:

- the region of lowest visibility in the 1970's was along the Ohio River Valley;
- the strongest increase in haziness occurred in the summer season in the States adjacent to the Great Smoky Mountains (a decrease in annual average visibility of 15 to 6 miles since 1948);
- around the Great Depression, the visibility at Blue Hill, Mass., improved, and two peaks of haziness around 1910-20 and 1940-50 coincide with two peaks of coal- and wood-burning. Likewise, a strong peak in turbidity corresponding to a decrease in visibility was present in the Madison, Wis. , data coinciding with the increase in national coal consumption. However, direct cause-effect relationships have not been established; and
- regional visibility in Eastern Canada and in both the Eastern and Western United States apparently has improved somewhat since 1972, but not to pre-1960 levels; whether this improvement relates to more favorable meteorology or reflects the slight reduction achieved in particulate and SO_2 emissions in the last 10 years is unclear.

[7] R B Husar, et al , "Spatial and Temporal Pattern of Eastern United States Haziness A Summary, " report prepared by the Center for Air Pollution Impact and Trend Analysis, Washington University, St Louis, Mo., for the U .S Environmental Protection Agency, 1981

* "National Oceanic and Atmospheric Administration/World Meteorological Organization

Case Studies: Southwestern United States

A number of factors combine to make visual ranges in the "four corners' region of the Southwestern United States a promising means of assessing the effects of sulfates on visibility. Pollutant concentrations and relative humidity levels in most parts of Arizona, New Mexico, Colorado, and Utah tend to be quite low; consequently, visibility levels are among the highest known throughout the United States, and changes in pollutant concentrations make significant differences in perceived visual ranges. In addition, over 90 percent of the region's sulfur emissions come from a single industry—copper smelters—which experienced a total shutdown during 1967-68, and a partial shutdown in 1980. However, ambient sulfate levels have not been monitored extensively in the region, as they have in the Eastern United States. Thus, while airport visual ranges show marked increases in these four States during the two copper-smelter shutdowns, relationships between sulfate and visibility have been difficult to establish.

Initial investigations found substantial decreases in sulfate levels at monitoring sites both near major smelting operations, and at remote areas up to 300 miles from the major smelting area in southeast Arizona, during the 1967-68 shutdown. [8] Visibility conclusions from this study have been criticized on the basis that sufficient data were lacking to document a consistent sulfate/visibility relationship. During a second strike in the summer of 1980, mean sulfate concentrations dropped to one-third of normal levels within 60 miles of the smelter; between 60 and 400 miles away, sulfate levels were about half of nonstrike conditions. Trajectory analyses of sulfate episodes in both the northern Great Plains and Grand Canyon areas show that some ultra-long-range transport from southern California occurs.

To further test the sulfate/visibility hypothesis, and to extend the information base on Southwestern visibility, an OTA contractor analyzed visual range and sulfate concentration data in 22 case studies covering pollution episodes and nonepisode periods before, during, and following the two shutdown periods. In addition, the RCDM long-range-transport model was used to estimate sulfate levels more generally over the ''four corners' region, and to provide preliminary estimates of the extent of sulfate contributions from sources outside the four-State region for the period 1979-81. The analysis strongly confirms the relationship among copper smelter emissions, sulfate levels, and visual ranges; in addition, it suggests that substantial portions of the sulfate levels measured during the 1980 shutdown can be traced to more distant sources, primarily those in southern California.

Modeling: Extinction Budget

While there are limitations in the use of regression models for determining extinction budgets and aerosol/visibility relationships, these techniques show that overall, sulfates account for over half (53 percent) of the extinction budget, nitrates account for only 8 percent, and a significant part of the budget is not accounted for at most of the sites analyzed. The nitrate contribution to the extinction budget is very uncertain (but small) due to uncertainties in the conventional nitrate filter-concentration measurements. More comprehensive studies of the extinction budget are needed, using special air quality and visibility measurements rather than relying on conventional air quality monitoring and airport data.

Sulfate was known to contribute significantly to light extinction 10 years ago. Subsequent efforts to determine the relative importance of nitrate and carbon to visibility impairment were hampered by measurement techniques and inherent spatial (urban v. rural) and temporal (seasonal) variability. There still is not enough high-quality data of nonsulfate measurements to generate complete regional budgets of the various pollutants' contribution to visibility impairment. Most recent information suggests that carbon may contribute to light extinction in heavily urban areas, such as Houston (17 to 24 percent of light extinction), Denver (about 40 percent of light extinction[10]), and New York (35 percent of light extinction"). Nitrate is an important factor in the West–e.g., in Riverside, Calf., it is responsible for about 20 to 25 percent of light scattering.[12] Nonetheless, at most Eastern U.S. sites, sulfate is the single most important pollutant responsible for visibility degradation. Under typical Eastern summertime conditions, sulfate accounts for 70 percent or more of light extinction in the Great Smoky Mountains, [13] the Shenandoah Valley, [14] and Detroit, [15] On an annual basis, sulfates contribute an average of about 50 percent to visibility impairment in the Eastern United States. [16]

[8] J C. Trijonis, ' 'Visibility in the Southwest: An Exploration of the Historical Data Base, *Atmos. Environ.* 13:833-43, *1979.*

[9] T. G. Dzubay, R. K. Stevens, C. W. Lewis, D. H. Hem, W. J. Courtney, J W. Tesch, and M. A. Mason, "Visibility and Aerosol Composition in Houston, Tex., *Environ Sci. Technol.* 16:514-525, *1982.*

[10] P. J. Groblicki, G. T. Wolff, and R. J. Countess, "Visibility-Reducing Species in Denver 'Brown Cloud'—I. Relationships Between Extinction and Chemical Composition, " *Atmos. Environ.* 15:2473-2483, *1981.*

[11] G. T. Wolff, P. J, Groblicki, S. H. Cadle, and R. J. Countess, "particulate Carbon at Various Locations in the United States, *Particulate Carbon: Atmospheric Life Cycle, G.* T. Wolff and R. L. Klimisch (eds.) (New York: Plenum Press, 1982).

[12] J. N. Pitts, Jr., and D. Grosjean, ' 'Detailed Characterization of Gaseous and Size-Resolved Particulate Pollutants at a South Coast Air Basin Smog Receptor Site' (Springfield, Va.: National Technical Information Service, #PB 302294, 1979).

[13] M. A. Ferman, G. T. Wolff, and N, A. Kelly, "The Nature and Source of Haze in the Shenandoah Valley/Blue Ridge Mountains Area, *J. Air Pollution Control Assoc. 31: 1074-1082, 1981,*

[14] R. K. *Stevens, T. G,* Dzubay, C. W. Lewis, and R. W. Shaw, Jr., "Source Apportionment Methods Applied to Determination of the *Origin* of Ambient Aerosols That Affect Visibilit, in Forested Areas, Atmos. Environment (in press).

[15] olff, et al, , op. cit.

[16] U.S Environmental Protection Agency, *Protecting Visibility, An EPA Report to Congress,* EPA 450/5-79-008, Research Triangle Park, NC., 1979,

B.5 HUMAN HEALTH RISKS*

Sulfur Oxides

National Ambient Air Quality Standards (NAAQS) have been established for gaseous sulfur dioxide (SO_2), recognizing that it is harmful to human health in high concentrations. The current primary standard for $S0_2$ is 365 µg/m^3 (24-hour average concentration), a level considered to pose no significant health risk. Though currently unregulated, concern also exists about health risks from sulfate particles—e. g., sulfuric acid and ammonium sulfate—that form through reactions between $S0_2$ and other substances in the atmosphere. Because these particles are extremely small (mostly under 1 µm in diameter), they can be transported over long distances in the atmosphere and can readily be inhaled into the deep passages of the lung.

Acute exposures to sulfates (greater than 315 µg/m^3) constrict lung passages and lengthen lung clearance-times in humans and laboratory animals; chronic exposure of laboratory animals to sulfuric acid mist produced evidence of the onset of chronic lung disease. In addition, numerous epidemiological studies have found correlations between ambient sulfate concentrations and mortality rates. Adverse effects at current ambient levels (less than about 25 µg/m^3) have not been directly observed.

Researchers at Brookhaven National Laboratory (under contract to OTA) have estimated that about 2 percent (a range of O to 5 percent) of the deaths per year in the United States and Canada might be attributable to atmospheric sulfur-particulate pollution. The range reflects uncertainties within the scientific community about the causal relationship between air pollution and mortality. Some researchers conclude there is a negligible effect at prevailing sulfate concentrations, while others have found a significant association with mortality.

Sulfur Dioxide

$S0_2$ emissions currently are regulated under the NAAQS of the Clean Air Act (CAA); the primary standard for $S0_2$ is 365 µg/m^3 (24-hour average concentration). Air pollution episodes characterized by particulate and very high levels of $S0_2$ have resulted in increased deaths in people with preexisting heart and lung disease. Changes in the function of the lungs have been seen in sensitive groups at concentrations above 5,220 µg/m^3. Recently, a study of asthmatics has shown that constriction of bronchial passages during periods of moderate exercise can occur at concentrations as low as 1,300 and 260 µg/m^3. [17]

Experimental Evidence of Sulfate-Related Health Damages

Once in the atmosphere, $S0_2$ is converted into sulfate particles. Two main types of sulfate particles are known to be produced: sulfuric acid (H_2S0_4) and ammonium sulfate [$(NH_4)2S0_4$]. Both types of particles are extremely small and may be inhaled deep into the lung. The high acidity of sulfuric acid particles make them of primary concern for medical researchers, although ammonia in human breath may neutralize sulfuric acid. Ammonium sulfate has not produced the pulmonary effects in animal and clinical studies that are seen with sulfuric acid mist.

In laboratory experiments, acute exposures to high concentrations of sulfuric acid particles have a variety of adverse health effects. Concentrations of about 750 µg/m^3 have irritated eyes and temporarily decreased vision; concentrations of 350 µg/m^3 have increased breathing rates and altered lung function in asthmatics. Changes in lung clearance rates have been observed in healthy nonsmokers at concentrations of 100 µg/m^3. Populations at special risk from particulate sulfates are the elderly and adults with preexisting chronic heart or lung disease. Children also appear to be especially susceptible to increased lower respiratory-tract illness and decreased lung function. However, there is no direct evidence showing detectable effects on human health from maximum likely environmental concentrations of sulfate particles alone, although laboratory and chemical studies have verified that these small sulfate particles concentrate deeper in the lung than larger inhaled particles. In addition, there is evidence that acid sulfates (and $S0_2$) render lung tissues more susceptible to the carcinogenic effects of polycyclic organic matter.

Evidence of Sulfate-Particulate-Related Health Damages

Substantial evidence has been gathered over more than 30 years indicating injury from some aspect of the sulfate-particulate mix in air pollution. At high exposure levels, sulfur-particulate air pollution can aggravate

*This appendix is based primarily on the OTA background paper "Long-Range Transport Air Pollution Health Effects," Biomedical and Environmental Assessment Divls.ion, Brookhaven National Laboratory, 1982

[17] D Sheppard, A.Saisho, J. A Nodel, and H A. Boushey, "Exercise Increases Sulfur Dioxide-Induced Bronchoconstriction in Asthmatic Subjects, *Am Rev Resp Dis* 123:486, 1981

asthma, chronic bronchitis, and heart disease.[18] There also is evidence that sulfur-particulate air pollution causes increased acute respiratory disease in children.

Many analyses of cities with different air pollution levels, comparing death rates among specific population groups, or cohorts, have shown strong correlations between pollution levels and mortality. Evidence is strongest for correlation between acute episodic effects and severe air pollution incidents; evidence of long-term effects at comparatively low levels of pollution is more limited and more controversial.

Nonetheless, scientists generally have been unable to attribute effects to any single element of the pollution mix. During the early 1970's, evidence seemed to point to sulfate particles as the health-damaging agent in the sulfate-particulate mix. More recent evidence suggests that the combination of sulfates and other associated particles such as metallic ions, nitrates, and fine soot particles may cause the observed effects.

Quantitative Estimates of Health Damages From Long-Range Transport Air Pollutants

To derive quantitative estimates of damage caused by long-range pollution transport, Brookhaven National Laboratory used sulfate concentrations as an index of the sulfur-particulate air pollution mix, acknowledging that its use in this manner remains controversial, but it is the best indicator of health risk currently available. Several reports have discussed problems with the use of the sulfate surrogate model. They indicate that other surrogates, e.g., respirable particles, may prove better but, at this time, the sulfur surrogate still remains a reasonable choice, and possibly the best choice, for air pollution health effects risk assessment. A detailed study by the Harvard School of Public Health for DOE concluded that a fine particulate (FP) measure would be preferable, but ''in the absence of FP data, . . . sulfates may be applied with caution. * The contractor used a previously developed health-damage function that specifically addresses uncertainties in knowledge by projecting a range of mortality estimates for a given population exposure level. * *

The health-damage function used is essentially a compilation of expert opinion about the relationship between sulfate pollution and premature mortality (e. g., due to aggravation of preexisting respiratory or cardiac problems). The range reflects a controversy over the validity of epidemiological (i.e., statistical) studies indicating a relationship between mortality and air pollution levels. It includes estimates from scientists who believe there is a negligible effect at prevailing sulfate concentrations as well as those believing there is a significant association.

These studies, carried out and extensively examined over the past decade, examine mortality statistics from areas of the country exposed to different levels of air pollution. The value of these studies is that they examine human health directly, without the necessity of extrapolating from animal studies or small samples of people. They indicate that there are regional differences in mortality, and that regional patterns of mortality are similar to air pollution patterns. While it is possible that factors not considered in these analyses may be more important than the sulfur-particulate mix, none have been demonstrated to date. Such studies are most useful for examining the potential effects of chronic, low-level exposure—what might be happening and what might result from future air pollution levels.

The mortality estimates developed for OTA assume that there is no damage threshold (i. e., minimum exposure level at which air pollution begins to affect mortality). If there is a threshold—which available medical evidence neither confirms nor refutes—the mortality estimates will decrease.

Sulfate-concentration data were derived from SO_2 emission inventories developed for the OTA study, using the Regional Climatological Dispersion Model (RCDM-2) developed at the University of Illinois–one of the models evaluated by the U. S, -Canadian Work Group on Transboundary Air Pollution. Population estimates and projections were derived from the U.S. Census Bureau and Canadian Ministry of Industry, Trade, and Commerce data.

Figure B-20 displays current State-by-State sulfate-exposure levels weighted by population. The map shows that some of the Northeastern States with the highest population density (e. g., New York, Pennsylvania, and Ohio) also are exposed to the highest ambient sulfate concentrations.

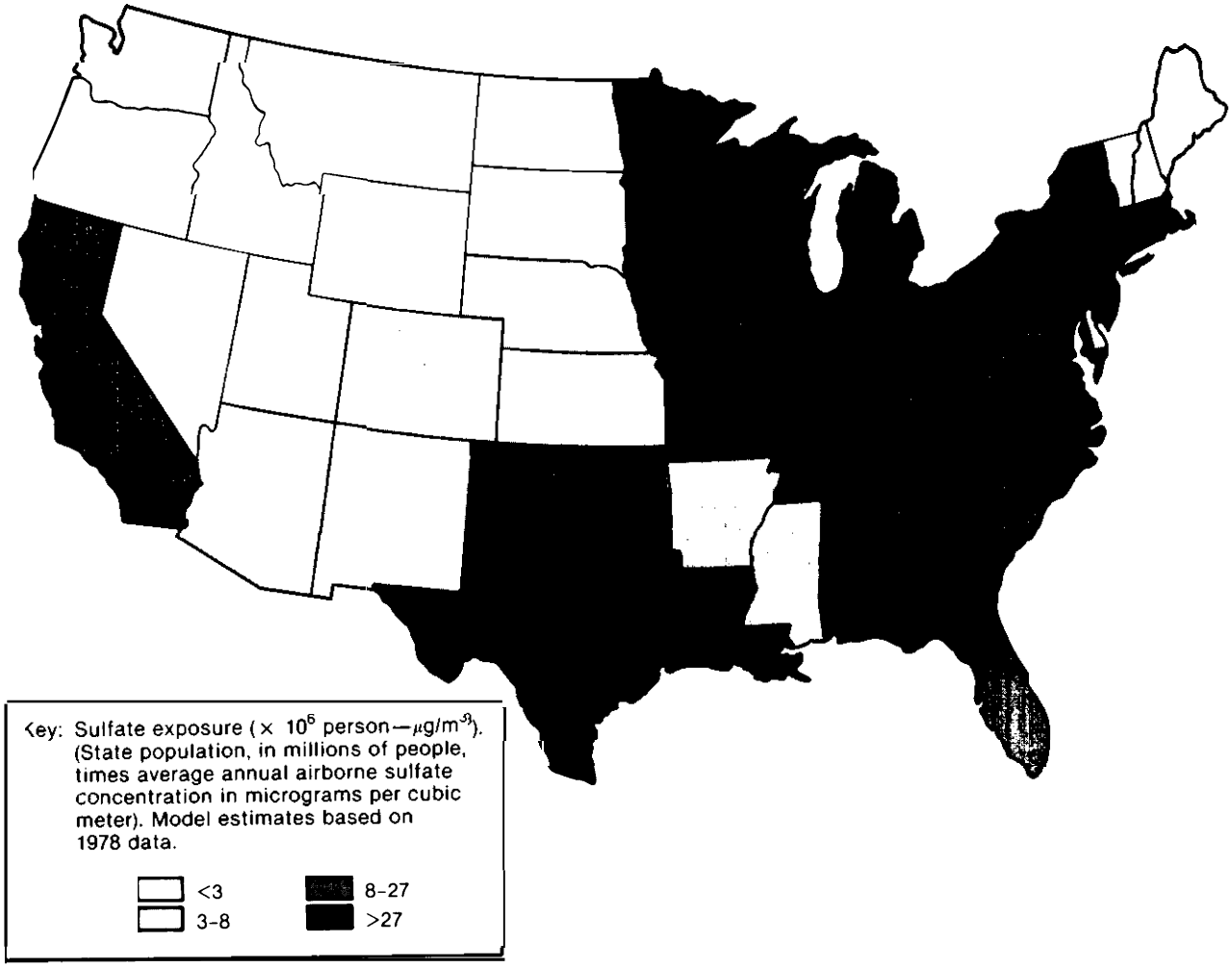
Estimates of excess deaths due to sulfate-particulate air pollution were made for: 1) 1980 population levels using 1978 emissions data; 2) populations in 2000, as-

[18] Environmental protection Agency, ' 'Review of the National Ambient Air Quality Standards for Particulate Matter: Draft Staff Paper, " Strategies and Air Standards Division OAQPS/EPA/RTP, January 1982; Lester B. Lave and E P. Seskm, *Air Pollution and Human* Health, 1977, Johns Hopkins University Press, Baftimore, Md. , Frederica Perera and A. K. Ahmed, *Respirable Particles:* impact *of* Airborne Fine Particulate on *Health* and the *Environment* (Cambridge, Mass.: Ballinger Publishing Co. , 1979).

* Spengler Final Report to DOE, October 1983, p. 5, and contribution of Spengler and Evans at DOE/HERAP Workshop on Health Effects of Air Pollution, Brookhaven National Laboratory, August 1982.

• *The function, developed by Morgan et al., is a probabilistic one with a 90-percent confidence interval of 0-11 excess deaths per 100,000 person-$\mu g/m^3$ sulfate exposure (i. e , deaths that would not occur in the absence of sulfate). M. G. Morgan, S. C Morris, A. K. Meier, and D. L. Shenk, "A Probabalistic Methodology for Estimating Air Pollution Health Effects From Coal-Fired Power Plants, " *Energy Systems and Pohcy* 2:287-310, *1978.* The current range of scientific judgment on the issue has not narrowed, but still spans the range of the 1978 subjective distribution (Morgan, M., et al., *Technological Uncertainty in Policy Analysis,* Report to the National Science Foundation, August 1982).

Figure B-20.— Population Exposure to Airborne Sulfate (an indicator of potential health effects from sulfates and other airborne particulate in each State)



SOURCE: Brookhaven National Laboratory, Biomedical and Environmental Assessment Division, "Long Range Transport Air Pollution Health Effects," OTA contractor report, May 1982.

suming that total emission levels are held constant at 1978 levels; and 3) populations in the year 2000, assuming that sulfate-particulate levels are reduced by 30 percent from 1978 levels. Results of these three scenarios are presented in table B- 14.

Total pollutant emissions in the United States and Canada have been estimated to result in about 50,000 premature deaths under the first scenario, increasing 1978 mortality rates by about 2 percent—an amount approximately equivalent to the number of deaths attributable to infectious lung diseases. While increases in population by 2000 would cause 1978 emissions levels to induce slightly higher levels of premature deaths (scenario 2), a 30-percent decrease in the overall sulfate-particulate mix by 2000 is estimated to reduce the number of deaths annually attributable to air pollution to about 40,000, or 1.6 percent of the total mortality rate.

Estimating mortality attributable to pollution exposure does not necessarily imply that the mortality impacts are the most significant. Mortality dose-response

Table B-14.—Summary of Scenario Results

Scenario	Population (millions)	Excess deaths total (10^3 deaths)	Range	Rate (deaths/10^5 population)
1.1980 population, 1978 emissions, United States and Canada	249	51	0-150	20.4
2.2000 population, emissions unchanged, United States and Canada	291	57	0-170	19.8
3.2000 population, sulfate-particulate mix 30% below 1978 levels, United States and Canada	291	40	0-120	13.8

SOURCE: Brookhaven National Laboratory, Biomedical and Environmental Assessment Division, "Long Range Transport Air Pollution Health Effects," OTA contractor report, May 1982.

functions are used because the available data on morbidity (illness) are inadequate for detailed epidemiological analyses.

Nitrogen Oxides

The term nitrogen oxides (NO_x) refers to a number of compounds—NO, NO_2, and such secondary byproducts as nitric acid, nitrate aerosols, and nitrosamines*—all of which have the potential to affect human health. Of the several NO_x compounds, by far the greatest amount is known about the effects of NO_2, a pollutant that has been studied over the past 30 years and is presently regulated under NAAQS.

The principal target of NO_x pollution is the respiratory system. Episodic or peaking concentrations of NO_2 (possibly augmented by NO) have been shown to cause immediate and short-term irritation to such sensitive subgroups of the population as asthmatics and individuals recovering from acute respiratory infections. Chronic exposure to lower concentrations of NO_2 has been associated with increased occurrence of acute respiratory infections in infants and children. Some scientists have hypothesized that such repeated low-level exposures also are associated with chronic lung disease and increased ' 'aging' of the lung in adolescence and adulthood.

Health effects directly attributable to NO_2 generally are considered to result from **localized** sources of pollution. Combustion of coal, oil, and gasoline is estimated to be responsible for local outdoor concentrations of NO_x 10 to 100 times naturally occurring background levels in areas of high emissions.** Indoor sources of NO_x, such as gas cooking stoves, some home heating systems, and cigarette smoking, also are known to contribute to population exposure, and in some cases may exceed outdoor concentrations of NO,.

Byproducts of NO_x are known to be transported over long distances, contributing to acid deposition and ozone formation. Some of these secondary pollutants are more toxic on a per-unit basis than NO_2; however, it is not currently known whether they are present in sufficient concentrations—or persist long enough—in the atmosphere to endanger human health. Recent studies performed for the EPA and the National Academy of Sciences suggest that nitrosamines and similar chemical species may be found in sufficient concentrations in polluted **urban** air near certain industrial areas to warrant concerns for health. Not enough is known yet about the effects of NO_x, or their concentrations in the atmosphere, to permit quantitative estimation of the health-related damages for which NO_x may be responsible, or of the population at risk from these pollutants.

Summary of Medical Research

Clinical studies of the short-term effects of NO_x on human volunteers have been conducted on asthmatics, patients with bronchitis, and healthy subjects. The studies generally have shown that the sensitivity of asthmatics to irritants such as cold air or air pollutants can be heightened by short-term concentrations of NO_2 as low as 940 $\mu g/m^3$ (the primary NAAQS for NO_2 is 100 $\mu g/m^3$ annually; there is no shorter term standard). Recovery from these effects tends to be rapid, and it is not known whether repeated exposures of this kind have any cumulative effects or predispose the lungs to permanent damage. Most studies do not show increased sensitivity or irritation in either healthy or bronchitis subjects when NO_2 concentrations are at or below 2,820 $\mu g/m^3$.

Laboratory experiments have tested the reactions of animal tissues to similar and higher concentrations of NO_2. These experiments have provided significant insight into the mechanisms that govern human reactions to NO_2 exposures, and suggest more serious consequences of long-term human exposure to NO_2 than have appeared in short-term clinical studies.

Prolonged exposure to NO_2 has been observed to cause damage to lung tissue in laboratory animals. The principal consequences of such damage appear to be de-

● These secondary byproducts are produced from photochemical transformation of NO and NO_2 in the atmosphere; nitrosamine formation has been theoretically suggested but not conclusively proven.

●● Mobile-source combustion was estimated to contribute 44 percent of anthropogenically produced NO, for 1976 in the United States, whife stationary-source combustion accounted for 56 percent. USEPA, *Air Quality Criteria for Oxides of Nitrogen,* June 1979, pp. 1-2 and 1-3,

velopment of emphysema-like conditions and reductions in resistance to respiratory infection. For a fixed dosage, greater concentrations have been shown to cause greater increases in mortality rates for animals exposed to respiratory infection than greater duration of exposure. This suggests that fluctuating levels of $N0_2$, such as are found in community air, may prove more toxic than sustained levels of the gas.

Epidemiologica1 studies of populations of children exposed to $N0_2$ concentrations, primarily via indoor air pollution, confirm laboratory findings of reduced resistance to respiratory infection in exposed animals. Children exposed to additional quantities of NO_2 (and possibly NO) from gas stove combustion—in particular, infants under the age of 2—show significantly greater incidence of acute respiratory illness and changes in lung function than counterparts living in homes with electric stoves. Similar findings have not been observed in adults.

Indirect Health Effects of Acid Precipitation

Acidified waters are known to be capable of dissolving toxic metals—e. g., aluminum, copper, lead, and mercury-and releasing such toxic substances as asbestos, from soils and rocks in watersheds and lakes, and from drinking water distribution systems. Researchers are attempting to determine the extent to which the total body burden of these substances in humans might result from acidic deposition, as opposed to direct inhalation or occupational exposure.

No direct relationship has yet been established between acid deposition and degradation of drinking-water quality. Potentially harmful levels of asbestos and lead, however, have been found in "aggressive' (i. e., corrosive) acidified waters in the Eastern United States. Scientists have encountered difficulty in pinpointing the direct source of concentrations of toxic materials found in acidic tap waters. Acidic precipitation can scavenge toxic materials from the atmosphere during rainfall events, leach them from soils and rocks as they pass through the watershed, or leach them from pipes and conduits used to distribute water to users.

The aggressiveness of municipal water supplies can be monitored and corrected fairly easily. A recent amendment to the National Interim Primary Drinking Water Regulations has established the initial steps in a corrosion control program.[19] Public water systems are now required to identify the presence of specific materials (e. g., lead and cadmium) within the distribution system and to monitor corrosiveness characteristics for at least 1 year. Also, the types of materials used in the distribution system and home plumbing must be reported.

A recent study sponsored by EPA[20] of 119 surface water supplies in the 6 New England States indicates that 84 to 92 percent of the water bodies are highly aggressive. Anti-corrosion treatment is currently practiced in specific areas (e. g., Boston) where acid precipitation is known to affect water quality. * However, aggressive well water in rural areas where soils have little capacity to counteract acid deposition is more difficult to detect and mitigate, and potential health effects remain of concern.

Asbestos

Asbestos occurs widely in natural rock formations throughout the east and west coasts of the United States. In addition, asbestos fibers are mixed in concentrations of 10 to 25 percent with cement to reinforce pipe used to distribute water supplies. While studies have shown that water can corrode asbestos-cement materials and release fibers into the drinking water, data showing a direct association between precipitation pH and asbestos content of drinking water are not available. However, preliminary estimates of asbestos in drinking water from asbestos/cement distribution pipes suggest that approximately 11 percent of the total U.S. population is exposed to asbestos concentrations greater than 10 million fibers/liter.[21]

Correlations between above-average incidence of certain abdominal cancers and elevated concentrations of asbestos in drinking water recently have been found in the San Francisco Bay area, where abundant natural supplies of asbestos occur in bedrock.[22] EPA has used data from studies of workers exposed to airborne asbestos to estimate that one additional cancer will be caused for every 100,000 people exposed to drinking water containing 300,000 asbestos fibers/liters for 70 years.**

[19] Environmental protection Agency. **Interim** Primary Drinking Water Regulations; **Amendment Final Rule, Fed. Reg 45(168). 57332-57357, Aug 27,** 1980

[20] Flovd **B.** Taylor, ' **'Impact of Acid Rain on Water Supplies in Terms of EPA Drinking Water Regulations,** ' *Proceedings of the American Water Works Association,* **Las Vegas, June 1983,** in **press**

"Boston has a high percentage of lead service lutes and plumbing. **During 1976-77, prior to** pH **adjustment, 44 percent of the top water samples exceeded the maximum contaminant level** (MCL) **of 0.05** mg/l **lead.**

"J R Millette, **M. F. Pansing, and R. L Boone, "Asbestos-Cement** Materials **Used in Water Supply,"** *Water Engineering and Management,* 128:48, **51, 60, 97, 1981**

[22] M.S **Kanarek, p. M Con** forti, **L A. <Jackson, R. C.** Cope l_, and J C Murchio, ' **'Asbestos in** Drinking **Water and Cancer Incidence m the San Franc isco Bay Area,** *Am J Epidemiol* , **112 54-72, 1980.**

*"**Federal Register 44(191) 56634,** Oct **1, 1979**

Lead

Lead enters aquatic ecosystems from wet and dry precipitation, mineral erosion, street runoff, leaded gasoline, and municipal and industrial discharge, as well as from corrosion of lead in pipes and plumbing systems. Corrosion of lead from lead-containing materials is facilitated by waters of low pH (less than 6.5) —especially when the waters are also of low alkalinity. Individual water samples in isolated areas characterized by low pH values have shown lead concentrations of up to 100 times the 50 µg/1 ambient water quality standard.[23] Early morning water samples from New England distribution systems showed 7 percent exceeded the standard for lead. 24

While elevations in human blood lead levels will result directly from ingesting contaminated drinking water, the human body also absorbs lead from a number of other sources, including food, ambient air, cigarettes, paint, dust, and dirt. *

Mercury

Studies in Scandinavia, Canada, and the United States have found correlations between elevated levels of mercury in fish and increasing acidity of lake and stream habitats. However, no cases of mercury poisoning are known to be associated with freshwater fish in the United States. Lakes in acid-sensitive regions of Minnesota, Wisconsin, and in the Adirondacks of New York have yielded fish with mercury concentrations above the FDA public health standard of 0.5 ppm.[25 26] Studies are currently under way to assess correlations between observed mercury levels and lake pH levels.

A number of recent efforts to neutralize acidic lakes through the application of lime appear to be successful in reducing mercury levels in fish. Favorable results have been reported for various locations in Sweden, and for Nelson Lake in Ontario, Canada.[27]

Other Metals

Acidified waters are known to leach substantial amounts of aluminum from watersheds, and the volubility of aluminum increases as pH decreases below 6.0. Concentrations of aluminum in acidified well water in the United States have been found as high as 1.7 mg/1, which could represent a substantial portion of an individual's daily aluminum intake. Little is known about the toxicity of aluminum to most human populations; no restrictions have been established in the United States on aluminum concentrations in drinking waters or foods.

Several studies have shown, however, that elevated aluminum concentrations may be toxic to individuals with impaired kidney function—e. g., water containing more than 50 µg/1 of aluminum is thought to be unsafe for dialysis treatment. Sixty-one percent of surface water samples in New England contained aluminum equal to or greater than 100 µg/l; 24 percent exceeded 200 µg/l.[28]

For normal human beings, copper deficiency is more widespread than copper toxicity. A limit of 1 mg/1 for copper concentration in U.S. drinking water has been set on the basis of taste; no regulatory limit exists for copper concentrations in food. Acidic waters have been shown to be capable of corroding copper from pipes in household distribution systems—elevated copper levels have been reported in several drinking water samples from sensitive areas of the Adirondacks. *g Additionally, a recent survey of New England distribution systems showed 29 percent of early morning water samples exceeded the standard for copper .30 While several cases of copper toxicity have been reported in the United States among individuals with Wilson's disease, a once-fatal disorder of copper metabolism, the hazard to the general population from currently observed copper levels appears quite small.

In its natural state, cadmium occurs as an impurity in zinc, copper-zinc, or lead-zinc deposits. In concentrated or pure form it is very toxic. Little evidence of cadmium corrosion from galvanized pipe or plumbing alloys currently exists, although studies of municipal wa-

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[23] P. Mushak *Multimedia Pollutants. Report to the National Commission on Air* Quality, 'Contract No, 232-AQ-6981, 1981; G. W. Fuhs and R. A. Olsen, ' 'Technical Memorandum: Acid Precipitation Effects on Drinking Water m the Adirondack Mountains of New York State, New York State Dept, of Health, Albany, N, Y., 1979.

[24] Taylor, F. B, op. cit

"EPA has defined approximately 2.5 million people-inner-city children under 5 and pregnant women—as being at special risk from elevated levels of lead in the bloodstream While aggressive drinking waters can leach lead from pipes and contribute to lead levels in the blood, such effects may constitute a greater threat to rural populations using acidified groundwaters than to urban populations using waters that can be treated readily, Preliminary investigations m the New York State Adirondacks region have found isolated cases of human exposure to lead-contaminated drinking water resulting in lead concentrations in blood as high as 59 µg/dl. (Blood lead levels should be maintained below 30 µg/dl to avoid deleterious health effects,) New York State Department of Health, Technical Memorandum: "Lead Poisoning Related to Private Drinking Water Sources, Oct. 23, 1981.

[25] *Acid* Precipitation in Minnesota, Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, Minnesota Department of Health, Jan. 26, 1982, pp. 7-67; Letter from G. Wolfgang Fuhs, Director, New York State Department of Health, to Congressman Toby Moffett, July 16, 1980, p. 3.

[26] Personal communication, James Wiener, U. S. Fish and Wildlife Service, La Crosse Field Research Station, La Crosse, Wis., May 1982,

[27] " The Role of Clouds in Atmospheric Transport of Mercury and Other Pollutants, " G. H. Tomlinson, R. J. P. Brouzes, R. A. N. McLean, and John Kadlecek, m Ecological *Impact ofAcid Precipitation,* Proceedings of an International Conference, Sandefjiord, Norway, Mar, 11-14, 1980, Oslo-As.

[28] Taylor, F. B. , op. cit.

[29] G. W. Fuhs and R. A. Olson, ' 'Technical Memorandum: Acid Precipitation Effects on Drinking Water in the Adirondack Mountains of New York, New York State Department of Health, Albany, 1979.

[30] Taylor, F. B. op. cit.

ter systems have shown levels to occasionally exceed the U.S. health standard of 10 µg/1. The concentrations found in drinking water, however, represent only a minute fraction of the amounts known to cause acute cadmium poisoning or chronic health effects under industrial exposure conditions. Based on the infrequent occurrence of cadmium in drinking water at levels above 10 µg/1, such exposures are not considered a threat to many people.

B.6 ECONOMIC SECTORS AT GREATEST RISK FROM CONTROLLING OR NOT CONTROLLING TRANSPORTED POLLUTANTS

Throughout this report, five sectors of the U.S. economy have been identified as sensitive to the potential effects of decisions to control or not to control transported air pollutants: 1) farming and agricultural services, 2) forestry and related products, 3) coal mining, 4) freshwater fishing-related recreation, and 5) the electric utility industry. This appendix presents information about the magnitude and geographic distribution of these activities in the Eastern 31 -State region. OTA assembled data from the Department of Labor, the U.S. Fish and Wildlife Service, and the Edison Electric Institute to estimate levels of economic activity for each, and levels of participation, where appropriate, in recent years. These tabulations are of total income, expenditures, employment, and resource utilization for a given sector. They are provided to indicate the relative importance of each sector to the economy and people of the Eastern 3 1-State region, not as estimates of the number of people or amount of economic activity that might be affected by decisions regarding transported air pollutants.

The amount of available information on the potential effect of controlling or not controlling transported air pollutants varies substantially among sectors. Moreover, for sectors dependent on resources potentially susceptible to transported pollutants, reliable estimates of the financial losses associated with resource damage cannot presently be attempted, even for resources for which damages can be estimated. Estimates of losses in crop production from ozone, and of the potential susceptibility of aquatic resources and forests to acid deposition, are provided in chapters 3 and 5, and are treated in detail in appendix B, section 2. Estimates of the economic effects of emissions control on coal mining and electric utilities, and of the coal-mining employment effects of emissions controls, are also presented in chapters 3 and 5, and detailed in appendix A. In general, the costs associated with emissions controls are better known than those associated with potential resource damage. As the available measures of potential effects are expressed in different forms, and represent disparate levels of knowledge, they cannot be compared directly across the five sectors. However, the importance of the economic sectors themselves can be compared, both in monetary and participatory terms, as well as among sectors and States.

Table B-15 presents State-by-State estimates of the personal income and expenses for which the five sectors directly account, in millions of dollars and as a percentage of the state total. U.S. Department of Labor data on wages, salaries, and proprietary income, averaged over the years 1978-80, are presented for farming and agricultural services, forestry and related products, and coal mining. Freshwater fishing-related recreation expenses are compiled from U.S. Fish and Wildlife Service survey data on expenditures for travel, lodging, food, fees, and light equipment used exclusively for fishing in 1980. For electric utilities, data from the Edison Electric Institute on the percentage of personal income spent on residential electricity consumption in each State are provided.

Farming- and forestry-related income each account for slightly less than 2 percent of the Eastern U.S. region total, or an average of $21.8 billion and $20.5 billion, respectively, for the 1978-80 period. Intraregional variations are significant: farming and agricultural services accounted for over 3 percent of personal income in Kentucky, Mississippi, Missouri, North Carolina, Vermont, and Wisconsin, and over 5 percent in Arkansas, Iowa, and Minnesota. Similarly, forestry, lumber, wood, and paper products accounted for over 3 percent of personal income in Alabama, Georgia, Minnesota, Mississippi, New Hampshire, South Carolina, Vermont, and Wisconsin, over 5 percent in Arkansas, and over 10 percent in Maine.

The greatest regional variation is found in the distribution of income due to coal mining, which accounted for an average of nearly $7 billion in the region during

Table B.15.-Income or Revenues From Farming, Forestry, Coal, Fishing, and Utilities
(in millions of dollars per year and percent of State total income)

	Farming agriculture and services		Forestry, lumber, wood, and paper products		Coal-mining		Freshwater fishing-related recreation		Utility revenues (residential only)	
Region/State	Income	Percent	Income	Percent	Income	Percent	Expenses	Percent	Revenues	Percent
New England:										
Maine	110.2	1.7	678.2	10.5	0.3	0.0	83.6	1.3	179.7	2.9
New Hampshire	27.3	0.5	208.1	3.6		0.0	36.2	0.6	166.8	2.9
Vermont	131.1	4.3	103.6	3.4	0.0	0.0	32.1	1.1	81.2	2.8
Massachusetts	48.9	0.1	687.9	1.6	0.3	0.0	86.3	0.2	830.0	1.9
Rhode Island	20.4	0.3	58.2	0.9	0.0	0.0	12.0	0.2	135.6	2.2
Connecticut	35.1	0.1	272.0	1.0	0.0	0.0	61.3	0.2	543.8	2.1
Middle Atlantic:										
New York	719.0	0.5	1,349.4	1.0	1.5	0.0	240.8	0.2	2,322.4	1.7
New Jersey	231.7	0.4	846.2	1.5	—	—	99.2	0.2	1,294.4	2.3
Pennsylvania	951.3	1.1	1,331.1	1.6	1,215.3	1.4	272.7	0.3	1,784.2	2.2
East North Central:										
Ohio	911.0	1.1	1,123.7	1.4	481.5	0.6	280.2	0.4	1,737.4	2.2
Indiana	1,017.1	2.5	641.7	1.6	210.3	0.5	268.7	0.7	839.0	2.2
Illinois	1,805.7	1.9	1,005.3	1.1	564.5	0.6	321.5	0.4	1,690.0	1.9
Michigan	779.9	1.0	767.7	1.0	1.3		394.9	0.6	1,197.4	1.7
Wisconsin	1,424.8	4.2	1,520.4	4.5	0.2	0.0	440.5	1.4	641.5	2.0
***West* North Central:**										
Minnesota	1,664.0	**5.3**	1,109.2	**3.5**	1.2	0.0	**383.5**	1.3	**504.8**	1.7
Iowa	1,670.7	**8.1**	171.4	**0.8**	8.7	0.0	**111.6**	**0.6**	**481.3**	2.5
Missouri	1,308.3	**3.7**	416.4	**1.2**	54.5	0.2	**301.6**	0.9	**807.9**	2.4
South Atlant/c:										
Delaware	116.2	**2.3**	—	—	0.0	0.0	7.8	0.2	**11.6**	2.3
Washington, D. C.	3.4	0.0	0.9	0.0	—	—	3.7	0.0	**229.6**	1.7
Maryland	265.9	0.9	261.1	0.9	28.2	0.1	61.1	0.2	**499.5**	1.7
Virginia	426.4	1.2	681.8	1.9	583.7	1.6	174.1	0.5	1,075.8	3.0
West Virginia	52.8	0.5	104.6	0.9	1,747.3	15.0	100.5	0.9	266.8	2.4
North Carolina	1,410.9	3.8	984.1	2.6	3.3	0.0	209.3	0.6	1,043.7	2.9
South Carolina	304.2	1.7	566.3	3.1	0.6	0.0	135.7	0.8	548.4	3.1
Georgia	760.0	2.1	1,149.7	3.2	1.9	0.0	300.8	0.9	903.2	2.6
Florida	1,564.5	2.7	736.4	1.3	1.3	0.0	483.9	0.8	2,377.3	4.1
East South Central:										
Kentucky	757.5	3.5	299.0	1.4	1,532.0	7.0	235.8	1.1	511.9	2.5
Tennessee	418.5	1.5	639.8	2.3	135.2	0.5	268.5	1.0	872.2	3.2
Alabama	661.3	2.9	979.9	4.3	389.2	1.7	285.8	**1.3**	765.5	3.5
Mississippi	650.9	5.0	564.3	4.4	0.1	0.0	170.3	1.4	434.5	3.5
West South Central:										
Arkansas	1,042.0	8.4	**639.2**	5.1	7.1	0.1	237.9	2.0	384.8	3.3
Louisiana	506.4	1.9	**644.2**	2.4	0.1	0.0	224.3	0.8	717.5	2.6
Eastern 31-State total	***...21.797.2***	1.9	**20,541.6**	1.8	6,969.7	0.6	6,326.2	0.6	25,980.3	2.3

SOURCES: U.S. Department of Labor; U.S. Fish and Wildlife Service, Department of the Interior; Edison Electric Institute,

1978-80, or 0.6 percent of the total. Nearly two-thirds of this income was earned in Kentucky, Pennsylvania, and West Virginia; coal mining accounted for over 1 percent of personal income in Alabama, Pennsylvania, and Virginia; 7 percent in Kentucky; and 15 percent in West Virginia.

Expenditure data for electrical power show that residential consumers spent nearly $26 billion to purchase electricity in the region in 1980. In general, the proportion of income spent on electricity is higher in Southern States, reflecting greater use of electrically powered cooling equipment. As a proportion of personal income, expenditures range from a low of 1.7 percent in the District of Columbia, Maryland, Michigan, Minnesota, and New York, to a high of 4.1 percent in Florida.

Freshwater fishing accounted for expenditures of approximately $6.3 billion in the region in 1980, or 0.6 percent of the region's total personal income. States in which these expenditures exceeded 1 percent of personal income included Alabama, Arkansas, Kentucky, Maine, Minnesota, Mississippi, Tennessee, Vermont, and Wisconsin. As shown in the table, freshwater fishing

generated at least $250 million in 1980 expenditures in 12 States: Alabama, Florida, Georgia, Illinois, Indiana, Michigan, Minnesota, Missouri, Ohio, Pennsylvania, Tennessee, and Wisconsin.

Table B-16 presents Department of Labor estimates of the number of people employed in farms and agricultural services, forestry and related products, and coal mining in 1980. In the Eastern region overall, agriculture employed slightly over 3 million people, or 4 percent of the regional total. Variations within the region are substantial—agriculture employed over 5 percent of the work force in Alabama, Indiana, Minnesota, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, Vermont, and Wisconsin; and over 10 percent of the work force in Arkansas, Iowa, and Kentucky.

Total Eastern employment in forestry, lumber, wood and paper products was slightly over one million, or 1.4 percent of the regional total. These industries employed

Table B-16.—Number of People Employed in Farms and Agricultural Services, Forestry and Related Products, and Coal Mining in 1980

	Farms and agricultural services[a]		Forestry, lumber, and wood and paper products[b]		Coal mining	
	Number of people	Percent of State total	Number of people	Percent of State total	Number of people	Percent of State total
U.S. total	4,628,300	4.3	1,404,000	1.0	251,000	0.2
New ***England:***						
Connecticut	20,436[c]	1.3	11,872	0.7	—	—
Maine	23,069	4.4	32,188	6.2	—	—
Massachusetts	25,670[c]	0.9	33,395[c]	1.2	—	—
New Hampshire	7,987	1.8	11,066[c]	2.5	—	—
Rhode Island	3,121	0.7	3,901	0.9		
Vermont	15,220	6.1	6,409	2.6	—	—
Mideast:						
Delaware	7,116	2.4	4,082[c]	1.4		—
District of Columbia	161	0.0	384[c]	0.1		—
Maryland	38,293	1.9	13,824	0.7	1,049	0.1
New Jersey	30,570	0.9	38,599	1.1	—	—
New York	117,351	1.5	64,965	0.8	—	—
Pennsylvania	118,613	2.2	63,580	1.2	37,911[c]	0.7
Great Lakes:						
Illinois	168,380	3.1	47,079	0.9	18,147	0.3
Indiana	134,314	5.3	32,791	1.3	6,060	0.2
Michigan	116,823	3.1	32,218	0.8		—
Ohio	154,279	3.2	52,404	1.1	15,490	0.3
Wisconsin	163,400	7.2	68,842	3.0		—
Plains Region:						
Iowa	177,130	12.3	8,464	0.6	—	—
Minnesota	161,453	7.6	43,415	2.0	—	—
Missouri	165,696	7.2	23,910	1.0	1,049	0.0
Southeast:						
Alabama	101,110	6.0	49,056	2.9	12,539	0.7
Arkansas	103,621	10.6	34,104	3.5		—
Florida	135,023	3.2	39,191	0.9		—
Georgia	119,319	4.6	59,375	2.3	—	—
Kentucky	154,212	10.0	16,749	1.1	47,319	3.1
Louisiana	72,610	3.9	28,516			—
Mississippi	104,257	9.6	31,218	2.9	—	—
North Carolina	177,556	6.1	57,191	2.0	—	—
South Carolina	76,427	5.1	30,150	2.0	—	—
Tennessee	144,397	6.7	37,106	1.7	4,184	0.2
Virginia	100,666	3.8	38,351	1.4	19,107	0.7
West Virginia	30,607	4.1	7,350	1.0	64,096'	8.6
Eastern 31-State total	***3,010,885 (65%)[d]***	4.0	1,020,724 (73%)[d]	1.4	227,252 (91%)[d]	0.3

aIncludes farm proprietors; excludes manufacture and sale of farm equipment.
bIncludes construction of prefabricated buildings and mobile homes; excludes manufacture of furniture, printing and publishing industries, and Sale of building materials,
c1980 data not available for all data points—estimates may be slightly low due to use of data from mid-1970's
dFigures in parentheses represent the proportion of the U.S. total employed within the Eastern 31-state region.

SOURCE: U.S. Department of Labor.

2 percent or more of the work force in Alabama, Georgia, Minnesota, Mississippi, New Hampshire, North Carolina, South Carolina, and Vermont, and 3 percent or more in Arkansas, Maine, and Wisconsin.

Employment in coal mining is the least evenly distributed of those sectors surveyed. It accounted for slightly under a quarter-million jobs, or 0.3 percent of the Eastern U.S. work force, in 1980. Coal mining employed greater than 0.5 percent of the work force in Alabama, Pennsylvania, and Virginia, and employed 3.1 and 8.6 percent of the work force in Kentucky and West Virginia, respectively. Estimates of shifts in coal mining employment that might accompany stricter SO_2-emissions controls are presented in appendix A.

The 1980 National Survey of Fishing and Hunting conducted by the Fish and Wildlife Service is the basis for estimates in table B-17 of the number of participants in freshwater fishing in the Eastern region. Counting only in-state fishing participants, to avoid double counting, over 21 million people are estimated to have taken part in freshwater fishing, devoting an average of somewhere between 11 and 21 days per year to this form of recreation. Counting only in-State residents, Florida, Georgia, Illinois, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin each had over a million freshwater-fishing participants; when out-of-State anglers are included, Alabama, Indiana, Kentucky, Missouri, North Carolina, and Tennessee are added to this list.

Table B-17.-Number of Residents and Nonresidents Participating in Freshwater Fishing in 1980[a]

	Number of residents	Total number of participants
Alabama	874,952	1,117,099
Arkansas	574,351	895,619
Connecticut	271,488	307,217
Delaware	30,221	35,136
District of Columbia	10,361	15,006
Florida	1,193,583	1,550,406
Georgia	1,117,544	1,253,265
Illinois	1,264,434	1,401,922
Indiana	913,212	1,111,095
Iowa	592,242	646,180
Kentucky	734,630	1,052,587
Louisiana	752,110	955,567
Maine	214,505	364,062
Maryland	268,716	321,687
Massachusetts	333,680	414,012
Michigan	1,292,682	1,666,295
Minnesota	1,175,026	1,639,131
Mississippi	538,349	689,901
Missouri	998,667	1,230,423
New Hampshire	115,357	224,998
New Jersey	229,175	383,375
New York	1,036,257	1,225,313
North Carolina	927,341	1,096,338
Ohio	1,412,022	1,500,525
Pennsylvania	1,168,907	1,400,689
Rhode Island	60,143	72,633
South Carolina	490,089	639,259
Tennessee	903,633	1,161,467
Vermont	113,256	182,753
Virginia	637,681	823,369
West Virginia	341,293	416,874
Wisconsin	1,109,738	1,674,219
Eastern 31-State total	21,760,645	[b]

aDoes not include fishing In the Great Lakes.
bTotal not calculated due to potential double-counting of participants.

SOURCE: U.S. Fish and Wildlife Service, Department of the Interior.