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Air Pollution Threats to US National Parks of the Great Lakes Region

by

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INTRODUCTION

The US National Parks and Lakeshores of the Great Lakes Basin are of special significance because they are accessible to the large population of much of the Midwest in no more than one day's travel. In comparison with most of the National Park System, this relatively close proximity permits much greater use and, therefore, more public interest in the sites, than is usual even for the general region. However, industrial development and related activities such as the generation of electricity, transportation, and urbanization, are also associated with this population. In turn, the products and residuals of the high population-density and industrial development have the potential for producing, through long-distance transport of pollutants, serious effects on the plants, animals, and visibility, in the parks.

This paper will review the principal qualities of the 'parks' (using that term in the wide sense to include all the categories involved), deal with the concentrations and transport of air pollutants in the region, and consider the prospective impacts of these pollutants on the parks' resource-base.

THE NATIONAL PARKS, MONUMENTS, AND LAKESHORES, OF THE REGION

Ten national parks, monuments, and lakeshores, have been designated in the Great Lakes region. The areas, locations, and general features, of these sites are summarized in Table I, which explains the initials used below after the individual names. The locations are shown by number code in the later Figures: seven sites are on the shores of the Great Lakes or are islands in the lakes, whilst three (Voyageurs N.P., St Croix N.S.R., and Cuyahoga Valley N.R.A.) are a slight to moderate distance from the lakeshores. The parks in the north-western portion of the region are characterized by wilderness features, while those in the southern part (Sleeping Bear Dunes N.L., Indiana Dunes N.L., Perry's Victory I.P.M., and Cuyahoga Valley N.R.A.) are located close to major population centres and are heavily used.

The Great Lakes region which these parks represent can be characterized primarily as having a continental climate, although the southern sections are dominated in

the summer by maritime tropical air originating from the Gulf of Mexico. The Great Lakes provide an important moderating effect along most of their shorelines; warm weather on shore areas in the spring is delayed in coming, but persists longer along the lakes in the autumn than inland. In addition, evening breezes from the lakes in the summer produce nights that are cooler than adjacent inland sites.

Six of the parks and lakeshores lie in the northerly portion of the region, and emphasize scenic vistas and wilderness-related uses (Fig. 1). The vegetation in the most northern sites is boreal coniferous forest, including Balsam Fir (*Abies balsamea*)*, White Spruce (*Picea glauca*), Paper Birch (*Betula papyrifera*), and Quaking Aspen (*Populus tremuloides*); White Pine (*Pinus strobus*) is a prominent species locally. In northern Wisconsin and the Upper Peninsula of Michigan, Eastern Hemlock (*Tsuga canadensis*), pines, and hardwoods such as Sugar Maple (*Acer saccharum*) and Yellow Birch (*Betula alleghaniensis*) dominate. Other hardwoods include Balsam Poplar (*Populus balsamifera*), Mountain-ash (*Sorbus americana*), Red Maple (*Acer rubrum*), and Mountain Maple (*Acer spicatum*). The characteristics of these six northerly units can be summarized as follows:

1. *Voyageurs National Park*:—covers 89,130 ha on the Laurentian Shield in northern Minnesota, and is the only 'conterminous' mainland US park that is characterized by boreal forest. The vegetation consists of fire-maintained spruce-fir, White Pine, and aspen-birch forests in the uplands, with Black Ash (*Fraxinus nigra*), White Cedar (*Thuja occidentalis*), and Black Spruce (*Picea mariana*), in low-lying areas.
2. *Grand Portage National Monument*:—287 ha on the shore of western Lake Superior near the US-Canadian border, marking the site of the eastern terminus of the eighteenth-century canoe portage from the inland waterways and western fur-trading regions.
3. *Isle Royale National Park*:—Consists of more than 200 islands in western Lake Superior totalling more than 230,000 ha in area. The heavily-glaciated rock-outcrops support both spruce-fir boreal forest and

* Scientific names are usually given only the first time an identified species is mentioned in the paper.—Ed.



FIG. 1. Long-distance visibility is, potentially, a prime amenity at virtually all of the US National Parks, Lakeshores, and Monuments, in the Great Lakes region. Here, in the high-visibility area of Lake Superior, Isle Royale National Park in Michigan can be seen on the horizon (30 km away) from a lookoff above Grand Portage National Monument in Minnesota. (Photo: O.L. Loucks.)

northern conifer-hardwoods forest. The Park is well-known for studies of its wildlife populations—particularly predator-prey relationship between Timber Wolf (*Canis lupus*) and Moose (*Alces alces*)*. Wilderness preservation is an important aspect of Isle Royale management.

4. *Apostle Islands National Lakeshore*:—Consisting of 17,010 ha along the southwestern Lake Superior shoreline in Wisconsin, valued for scenic vistas and near-pristine conditions. The one-quarter-mile (ca 400 m) extension of park jurisdiction into the lake around the islands protects spawning shoals for Lake Trout (*Salvelinus namaycush*) and whitefish (*Coregonus* and *Prosopium* spp.), which provide one of the most productive commercial and recreational fisheries in Lake Superior.
5. *St Croix National Scenic Riverway*:—Totalling 25,380 ha combining the St Croix National Scenic Riverway and the Lower St Croix National Scenic Riverway. The outstanding features of the Riverway are the St Croix and Namekagon Rivers and their riparian environments. The vegetation ranges from pine and northern hardwood forests to marshes and conifer swamp. Bluffs and gorges are frequent along the rivers. The mid-continent location makes the Riverway an attractive habitat for White-tailed Deer (*Odocoileus virginianus*), Black Bear (*Ursus americanus*), Wolf (*Canis lupus*), and Bald Eagle (*Haliaeetus leucocephalus*).

* and also, we recall from our student days of interest in plant succession, as the site of one of the few fairly long-term studies then known of 'Seventeen Years of Successional Change on Isle Royale, Lake Michigan' (I think the title was).—Ed.

6. *Pictured Rocks National Lakeshore*:—Consisting of 28,910 ha on the southern shoreline of Lake Superior in Michigan's Upper Peninsula. The site is focused around precipitous granite outcrops, beaches, and dunes. Forests surrounding the shoreline are classified as Hemlock-White Pine-northern hardwoods, but wet sites support White Cedar, Black Spruce, and Tamarack (*Larix laricina*). Numerous inland lakes and rivers with rapids and waterfalls are also included.

The four more intensively-used parks are located in the southern part of the Great Lakes Basin and are representative of two forest regions—Hemlock-pine-northern hardwood (Sleeping Bear Dunes N.L. and Indiana Dunes N.L.) and Maple-Beech (*Fagus grandifolia*-Basswood (*Tilia americana*) (Perry's Victory I.P.M. and Cuyahoga Valley N.R.A.). All these parks are relatively close to metropolitan areas: their outstanding features can be summarized as follows:

7. *Sleeping Bear Dunes National Lakeshore*:—Established in 1970 on the eastern shore of Lake Michigan, this site features two large dune complexes on the mainland shore of Lake Michigan and two off-shore islands. The mainland area includes conifer-hardwood forests and two canoeable rivers.
8. *Indiana Dunes National Lakeshore*:—Located on the southeastern shore of Lake Michigan, east of the Chicago metropolitan area, this site features extensive post-Pleistocene dune complexes, and early-successional vegetation types including oaks (*Quercus* spp.) and Jack Pine (*Pinus banksiana*). The site also includes extensive wetlands and peat bogs of historic significance for North American ecology (e.g. Cowles, 1899).

Table I
National Park, Monument, and Lakeshore, Sites in the Great Lakes Region of the United States*.

Park/Monument/Lakeshore	Area (km ²)	Location	Features/Resources
1. Voyageurs National Park	891	Northern Minnesota	Forest wildlife, beach shore; dunes; lakes, national and historic landmarks
2. Grande Portage National Monument	3	Northeastern Minnesota: western shore of Lake Superior	Forests; lakes and streams; exhibits
3. Isle Royale National Park	2,313	Northwestern Lake Superior (Michigan)	Islands; forests, wildlife, Biosphere Reserve; historic sites
4. Apostle Islands National Lakeshore	170	Northern Wisconsin: southwestern shore of Lake Superior	Island shorelines; forests
5. St Croix National Scenic Riverway	254	Northwestern Wisconsin and adjacent Minnesota	State forests; state parks; rivers; trout streams; national natural landmarks; wildlife
6. Pictured Rocks National Lakeshore	289	Northern Michigan, on southeastern shore of Lake Superior	Beach shore; scenic vistas; dunes; forests; lakes; rivers; historic sites
7. Sleeping Bear Dunes National Lakeshore	288	Western Michigan, eastern shore of Lake Michigan	Beach shore; dunes; rivers and streams; wildlife
8. Indiana Dunes National Lakeshore	51	Northern Indiana: southern shore of Lake Michigan	Beach shore; dunes; national and historic landmarks
9. Perry's Victory National Monument & International Peace Memorial	0.1	Northern Ohio, on western Lake Erie shoreline	Monument and observation platform for island vistas; also viewed from boat tours and Ohio shoreline
10. Cuyahoga Valley National Recreation Area	129	Northern Ohio, southeast of Cleveland	Forest; river; remnants of national and cultural heritage

* Locations are indicated by their (above) numbers on the sketch-maps (Figs 3 and 4).

9. *Perry's Victory National Monument and International Peace Memorial*:—A site and monument on South Bass Island in western Lake Erie (15–20 km from the Ohio shoreline), and approximately 55 km east of Toledo, Ohio. The actual Monument is 107 m in height and includes an observation platform for viewing the western Lake Erie Islands. Access is by boat tour, although the Monument is readily seen from the Lake Erie shoreline.
10. *Cuyahoga Valley National Recreation Area*:—Located along the Cuyahoga River Valley between the Cleveland and Akron metropolitan areas, this park represents diverse topographic features and a biogeographic interface between northeastern mountain and western oak–hickory (*Carya* spp.) forest provinces. Deciduous forests with a mixture of pines and Eastern Hemlock cover nearly half of the park. The Hemlock locally makes up a coniferous forest in the ravines and isolated wetland areas.

POLLUTANT SOURCES AND AIR QUALITY IN THE REGION

The Clean Air Act of the United States, and the regulations established to implement it, defines ‘criteria pollutants’ for which ambient-air quality standards have been promulgated. It also recognizes other pollutants which may be regulated by other means than the setting and maintenance of standards. The criteria pollutants are sulphur dioxide (SO₂), nitrogen oxides (NO, N₂O, and other oxides, usually cited as NO_x), total suspended particulates (TSP), and ozone (O₃). As the last two are

formed in large part by reactions in the atmosphere, a distinction must be made between primary emissions—some of which can produce direct effects upon organisms or materials—and secondarily produced pollutants such as sulphate (SO₄⁼), total suspended particulates, O₃, and acidic deposition. Other primary emissions include fluorine, heavy-metals, and numerous volatile organic compounds. When major sources of these pollutants are found upwind of sensitive species of plants, the potential exists for primary pollutant effects. But in more remote areas, a greater potential exists for effects from pollutants formed during transport. The former situation would occur principally near urban or industrial areas, and the latter at any site over which pollutants could be carried.

The problems of pollutant sources and ambient concentrations can be considered from several perspectives. The principal sources of (A) SO₂ and (B) NO_x for the region are shown in the two parts of Fig. 2. The SO₂ sources are located in the urban centres and industrial sites along the Ohio River Valley, while the NO_x sources correspond to the major urban centres. Ambient concentrations associated with the release and transport of these pollutants have been summarized in several reports by the Council on Environmental Quality (1978, 1979, 1980). In 1978 (Council on Environmental Quality, 1980), 79% of the 67 counties in Region V* with O₃ monitors were in violation of the National Ambient Air Quality Standards

* The Environmental Protection Agency’s (EPA’s) Region V comprises Minnesota, Wisconsin, Illinois, Michigan, Indiana, and Ohio.

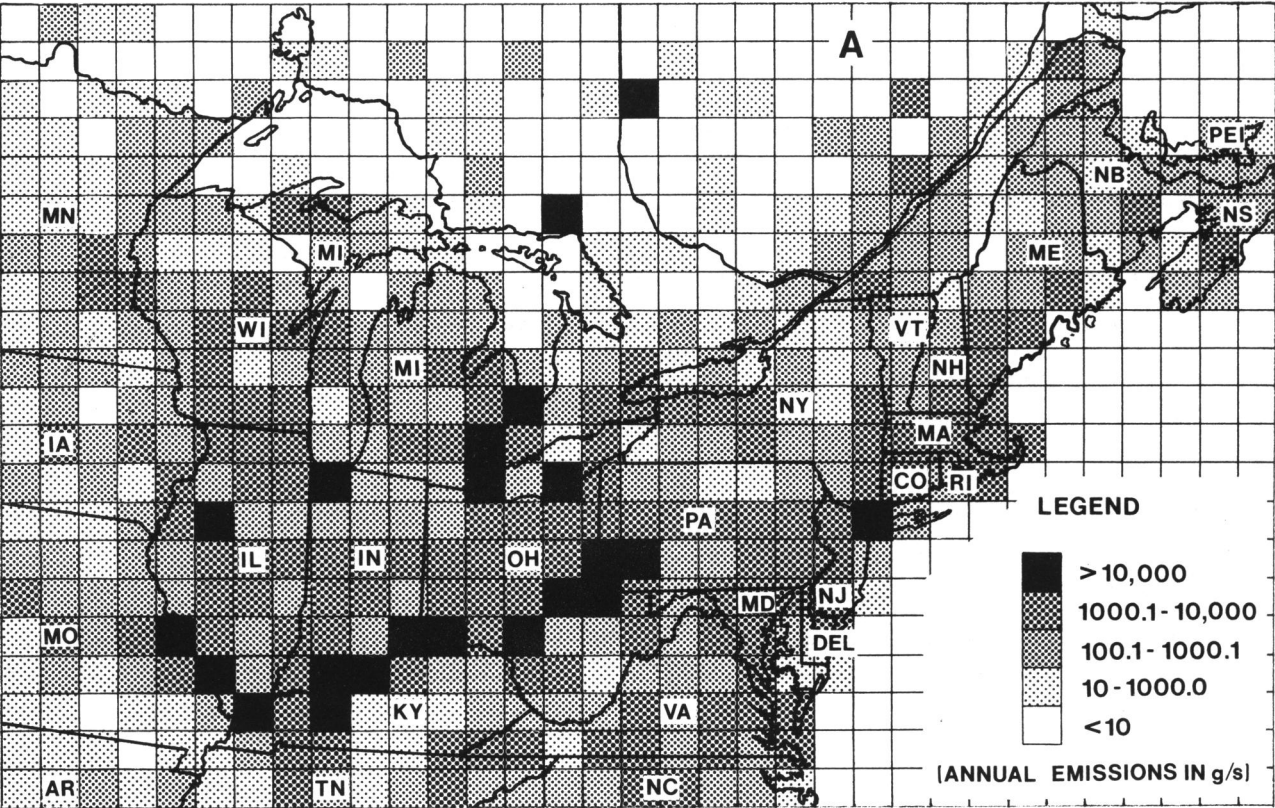


FIG. 2. The magnitude of (A) total annual SO_2 emissions, and (B) total annual NO_x emissions, in eastern North America. The data are in grams per second (g/s). Summarized from Environment Canada and SURE II data bases (US/Canada, 1979). The scale is approximately 1 cm to 150 km.

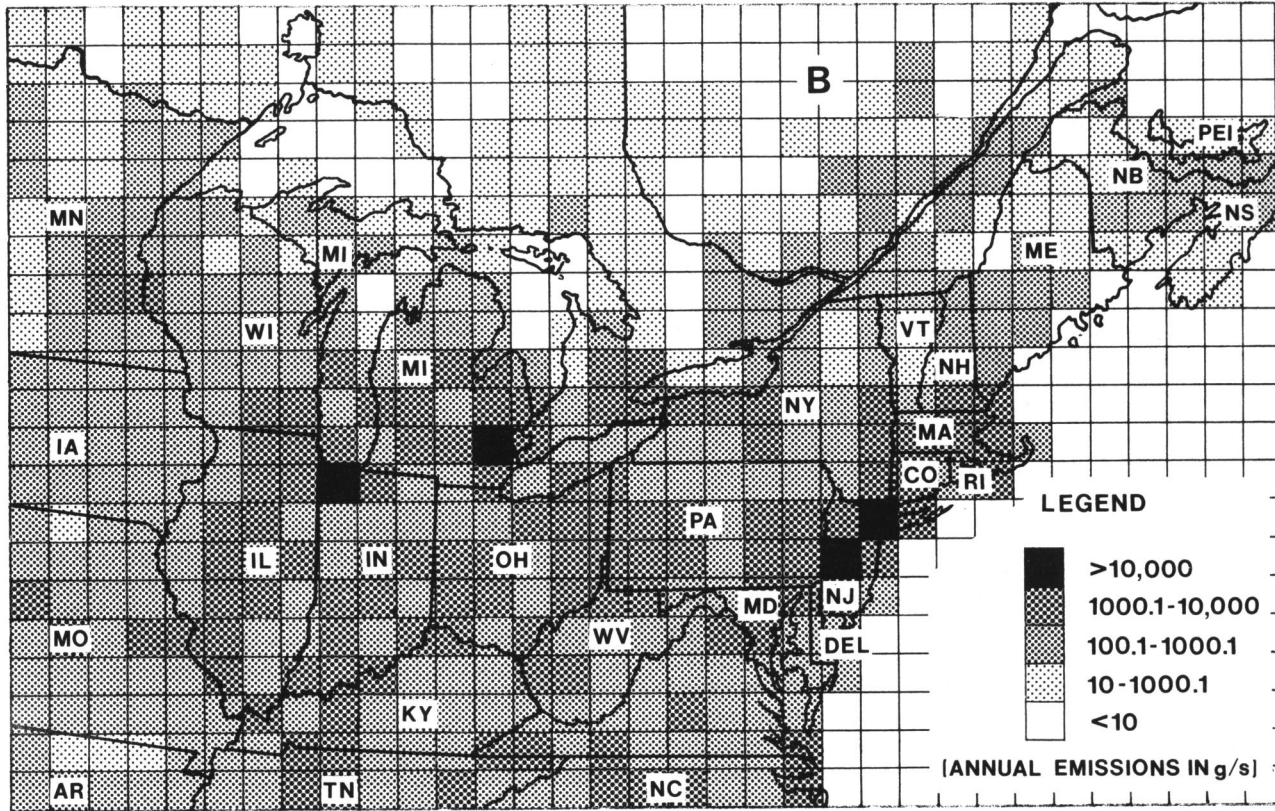


TABLE II
Summary of Pollutant Exposure Data for Urban Areas in the Southern Great Lakes Region.
(Data are from Council on Environmental Quality [1978, 1979] and apply to 1977 except as indicated.)

Site	SO ₂ No. days 24 hr $\bar{x}$ between		O ₃ No. days maximum hourly $\bar{x}$ between		TSP No. days 24 hr $\bar{x}$ between	
	0.14 and 0.31 ppm	0.31 and 0.61 ppm	0.12 and 0.20 ppm	0.20 and 0.40 ppm	260 and 375 $\mu\text{g}/\text{m}^3$	375 and 625 $\mu\text{g}/\text{m}^3$
Milwaukee, Wisconsin	4	0	15	1	5	4
Chicago, Illinois	3	0	18	5	13	10
Gary, Indiana area	11	0	9	1	8	0
Toledo, Ohio	7	0	5	0	2	0
Cleveland, Ohio (1976)	19	2	Not Available		23	8
Akron, Ohio	0	0	13	0	0	0
Buffalo, NY	1	0	11	0	21	3

for O₃ (0.12 ppm); 14% of the 160 counties monitored for SO₂ were in violation of the SO₂ primary standard (0.14 ppm averaged over 24 hours); and 27% of the 122 counties monitored for total suspended particulates were in violation of the primary standard (260 $\mu\text{g}/\text{m}^3$ averaged over 24 hours). These data originate in counties which are predominantly urban or suburban in character, and hence similar to the general environment of the parks in the southern part of the region.

Other data from the Council on Environmental Quality (1978, 1979) show the frequency with which the National Standards are exceeded at monitoring stations in seven urban areas along the southern Great Lakes (Table II). These results are in terms of primary standards, with 24-hours' averaging times (appropriate for human health responses). Secondary standards, based on 3-hours' averages which represent the short-term peaks in pollutant concentrations that affect crop and forest species, have been established for SO₂ (0.5 ppm) and TSP (150 $\mu\text{g}/\text{m}^3$); but violations tend to be too frequent for summaries to be useful. In the case of SO₂, the logarithmic distribution of concentrations in relation to the proportion of time that concentration is exceeded, indicates that 24-hours' averages of 0.14 ppm (the primary standard) involve frequent 3-hours' averages between 0.5 and 1.0 ppm. The comparative data from a site in the Boundary Waters Canoe Area of the Superior National Forest of northern Minnesota (Table III) show SO₂ to be negligible, but O₃ and TSP are high for such a remote site.

LONG-RANGE TRANSPORT AND CHEMICAL
TRANSFORMATION OF POLLUTANTS

Regulations promulgated under the Clean Air Act established 'Air Quality Control Regions' (AQCRs) as the geographic unit within which US air quality improvement strategies would be designated and evaluated. Air quality measurements within each region are used to determine 'attainment status' with respect to national ambient-air

quality standards for that AQCR. These procedures focus control on local, ground-level pollution problems associated in large part with primary emissions of SO₂, NO_x, and suspended particulates. Although O₃ is known to be a secondary product (as are sulphate particulates) formed during a period of residence in the atmosphere, strategies for their control are also attempted from within the AQCR. Because of long-range transport of pollutants, however, these strategies have been only partially successful, and reduced air quality is being observed increasingly over areas that are remote from any local sources (Council on Environmental Quality, 1979).

Although primary pollutants are associated with high densities of industrial and vehicular sources along the southern shores of Lakes Michigan, Huron, and Erie, chemical transformation of pollutants and long-distance transport is producing elevated levels of total particulates, photochemical oxidants (chiefly O₃), and acidic deposition, at remote sites—including the most northerly of the National Parks and Monuments treated in Table I.

The fate of primary emissions released into the atmosphere depends on several factors, some of which are meteorological but others are concerned with properties of the pollutants themselves. Prolonged reaction-times and long-range transport are facilitated by tall stacks,

TABLE III
Summary of Available Data from the Superior National Forest in Northern Minnesota (Fernberg Road Site).
(Data from the Minnesota Pollution Control Agency, reported by Glass & Loucks [1980].)

SO ₂ Individual hourly readings Feb.–Dec. 1977	O ₃ Hourly maximum May–Dec. 1977	TSP 24-hr maximum Feb.–Dec. 1977
≤0.004 ppm	0.10 ppm	66 $\mu\text{g}/\text{m}^3$

high wind, a stable lower atmosphere (i.e. where the temperature does not increase rapidly with altitude), and the absence of precipitation. All of these are frequent in varying degrees throughout the region, and are affected by the presence of the large, stable lake surfaces.

The meteorological factors governing long-distance transport are primarily those associated with clockwise circulation of air around high-pressure systems and the counter-clockwise flow of low-pressure centres. These winds tend to facilitate transport from south to north in advance of frontal systems, and from north to south behind them, while the prevailing weather systems move from west to east and from south-west to north-east. Occasionally, following quiescent high-pressure systems in the eastern US, major incursions of polluted air originating in the Ohio River Valley move into northern Minnesota, Wisconsin, and Michigan. Hence, primary emissions from a large area in the industrialized Midwest are the precursors of the elevated pollutant concentrations and acidic deposition that are observed in the northern Midwest and the US north-east.

Episodes of elevated O_3 concentrations in the eastern United States are associated with slow-moving, warm high-pressure systems which move out of the US western high plains and travel eastwards into the Midwest. As each system moves out of a relatively pollutant-free area of the northern Rocky Mountains or Canada, it contains between 30 and 50 parts per thousand million (ppb) of O_3 . Additional O_3 is formed from reactions involving NO_x and hydrocarbons, and despite some scavenging by vegetation, the products accumulate within the air-mass (Wolff *et al.*, 1980). Air-mass stagnation occurs occasionally, and O_3 concentrations from three to eight times as great as the natural background are observed (Wolff *et al.*, 1980). For example, an episode in August 1976, lasting over 10 days, was associated with a high-pressure system centred over western Lake Michigan. Ultimately, it affected nearly the entire eastern United States. Although the high O_3 levels near the southern part of Lake Michigan (Table II) may originate in part from local precursor sources, long-distance transport processes can bring elevated O_3 concentrations into the remote, wilderness-related parks sites. Similar episodes can occur from a few to a dozen or more times annually (Lioy & Samson, 1979), depending on meteorological conditions.

Thus, considering the combination of local sources and long-distance transport, the air pollution threats to resource values of the Great Lakes parks range from the direct effects of SO_2 emissions, on to effects associated with visibility reduction (from particulates, primarily SO_4^{2-}), the effects of O_3 on terrestrial vegetation, and the impacts of acidic deposition on poorly-buffered watersheds, lakes, and streams. These will now be discussed in turn.

OZONE, SO_2 , AND THEIR EFFECTS

Photochemical oxidants, primarily O_3 , are recognized as the air pollutant causing the economically most significant losses to agriculture in the United States (Hileman, 1982). Reports of reduced yields of crops come from as far north as central Minnesota (Kohut *et al.*,

1977). Reduction of crop yields can also occur at the SO_2 concentrations cited in Table III for counties in and around the urbanized areas of the southern and eastern Great Lakes.

Effects on native vegetation have seldom been estimated quantitatively on a regional scale, but recent evidence shows that sensitive native trees are affected by regionally elevated O_3 concentrations in forested areas far from any large pollutant sources. Treshow & Stewart (1973) observed that 24 out of 70 common native species were visibly injured by exposure to 0.25 ppm or less O_3 for two hours. These authors suggested that growth and community vigour can be impaired in affected ecosystems by repeated, long-term exposures to even much lower concentrations.

Field studies of forest responses to SO_2 indicate that repeated exposures at levels seldom exceeding 0.2 parts per million (ppm) for only half-hour periods have led to wood production losses in coniferous forests (Legge, 1980). As noted above, the National Ambient Air Quality standard is 0.5 ppm, averaged over a 3-hours' period. Exposures at 0.05 to 0.1 ppm SO_2 for a few hours cause leaf injury and reduced needle-length in sensitive species such as eastern White Pine (*Pinus strobus*), particularly when applied in conjunction with regional ozone exposure that is only moderately above background (Dochinger *et al.*, 1970; Houston, 1974).

Differential mortality of White Pine strains was associated with genetic differences in pollution sensitivity in populations near to a rural central-Wisconsin power-plant (Karnosky, 1980). The SO_2 and O_3 exposures were low in comparison with national air-quality standards, but foliar expression of air pollution injury was found in sensitive trees in 15 separate plots, and mortality rates of sensitive trees was from twice to five times as high as in more resistant strains.

Synergistic effects of the two gases (SO_2 and O_3), such as appear to have been expressed in the study of Karnosky (1980), could explain the occurrence of effects at the relatively low pollutant concentrations (Dochinger *et al.*, 1970). However, in other forest areas, O_3 -damaged trees have been found in the absence of known SO_2 sources. Thus, the increased mortality in White Pine observed over several years in Shenandoah National Park, Virginia, and in nearby states in areas remote from large pollutant sources, is attributed to O_3 impacts and long-distance transport (Skelly *et al.*, 1979).

Evidence for O_3 - and SO_2 -induced disease symptoms in White Pine from a geographic cross-section within the southern Great Lakes region has been presented by Usher & Williams (1982). Their observations on foliar mottling and flecking, length of tip-necrosis and tip-burn, and loss of second-year foliage—all of which are disease symptoms associated with gaseous pollutant exposures—are summarized in Table IV. Their data are drawn from four stands that were sampled in south-central Wisconsin and nine in central and southern Indiana. Although the SO_2 levels which they cite were high enough to interact synergistically with O_3 in the urban areas of their study, the occurrence of typical foliar injury symptoms at rural Wisconsin and Indiana sites was attributed primarily to the elevated regional O_3 exposures.

TABLE IV
Percentage of Eastern White Pines at Sites in Indiana and Wisconsin with Symptoms Attributable to Air Pollution.
(After Usher & Williams, 1982.)

Symptom	Trees with symptoms, %	
	Indiana, 1979-80 (n = 457)	Wisconsin, 1980 (n = 120)
Chlorotic mottling/flecking on most needles:		
None to very slight	40.9	92.5
Slight and moderate	49.9	7.5
Severe	9.2	0.0
Length of tip-necrosis on most needles:		
None to 1 mm	46.1	93.8
1-5 mm	45.8	5.0
> 5 mm	8.1	0.0
Second-year needles retained:		
None	55.8	18.3
1-19%	30.8	30.8
20-100%	13.2	50.8

Personal observations by one of the present Authors (O.L.L.) at many of Usher & Williams's study-sites, and in National Monuments/Lakeshores in Minnesota, Wisconsin, and Indiana, indicate effects on White Pine that are consistent with the results shown in Table IV. Open-grown White Pine in the Indiana Dunes National Lakeshore show the greatly reduced retention of needles and partially necrotic foliage evident in the Indiana data of Usher & Williams (1982). Partial mortality of the upper canopy, and early mortality of some trees, is also evident. In the Apostle Island National Lakeshore and Voyageurs National Park, foliage symptoms and needle retention are generally better than at the sites in south-central Wisconsin. Needle retention, however, was not observed on third-year twigs at these locations, although needles are present on such twigs on herbarium specimens collected several decades ago—a response that seems consistent with the moderate O₃ exposures at these northern sites.

Other tree species in the parks of the Great Lakes region, which have been demonstrated experimentally to suffer reduced growth at the moderate concentrations of O₃ observed in large portions of the area, include Quaking Aspen, Sycamore (*Platanus occidentalis*), Red Maple, and Green Ash (*Fraxinus pennsylvanica*) (Townsend & Dochinger, 1974; Karnosky, 1976; Kress & Skelly, 1982). Thus, oxidant effects seem now to be occurring—not only on numerous species in forests of the more polluted southern and eastern National Park sites, but perhaps also on the most sensitive species in the northern sites. Additional research is needed to document these relationships fully in the field.

VISIBILITY REDUCTION

Numerous studies have demonstrated that atmospheric reactions involving SO₂, NO_x, O₃, and ammonium, contribute strongly to the formation of aerosol-sized particulate matter—primarily various forms of ammonium sulphate and nitrate particles. During periods of slow-moving anticyclonic activity, these reactions, combined with uptake of water by the particles from humid air-masses, lead to increased haze and visibility reduction (Fig. 3) over most of the eastern US (US Environmental Protection Agency, 1979). In the Ohio Valley states, visibility is now often reduced to two miles (3.3 km) or less during air stagnation episodes and sulphate-induced morning fog, seriously reducing the scenic value of both the state and the national parks. Visibility reduction owing to high concentrations of sulphate occurs occasionally in the northwestern portion of the region (particularly in August of 1982), and these episodes are reflected in the intermediate visual range shown in Fig. 3.

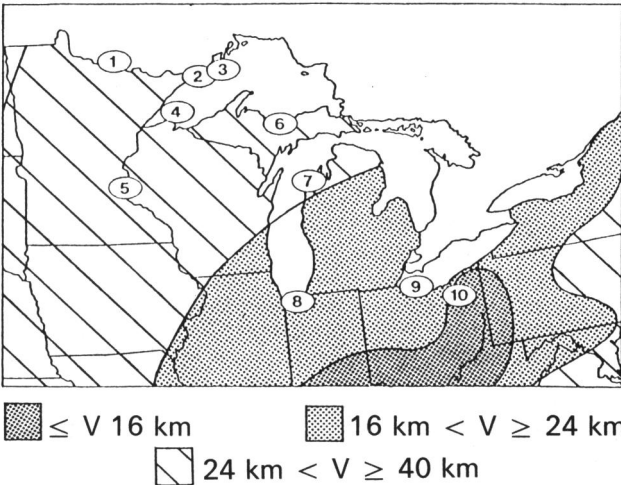


FIG. 3. Visual range (V) isopleths for non-urban areas in the Great Lakes region, 1974-76. Visual range in northwestern Minnesota falls between 25 and 45 miles (40 and 56 km). Adapted from Trijonis & Shapland (1978). Locations of parks etc.: 1 = Voyageurs N.P.; 2 = Grand Portage N.M.; 3 = Isle Royale N.P.; 4 = Apostle Islands N.L.; 5 = St Croix N.S.R.; 6 = Pictured Rocks N.L.; 7 = Sleeping Bear Dunes N.L.; 8 = Indiana Dunes N.L.; 9 = Perry's Victory N.M.; 10 = Cuyahoga Valley N.R.A. The scale is approximately 1 cm to 240 km.

Various substances contribute to atmospheric haze, which develops through a combination of reflection of sunlight and light-scattering properties of particles. Although natural sources of fine particles such as dust and water vapour contribute somewhat to visibility reduction, most studies suggest that the reduced visibility is attributable mainly to the SO₂ and NO_x sources and the long-distance transport of the resultant aerosol particulates (Weiss *et al.*, 1977; Ferman *et al.*, 1981). Major increases in SO₂ emissions over the past several decades (National Research Council Committee on the Atmosphere and the Biosphere, 1981), have led to the reduction in visibility over the eastern United States, including the

entire Great Lakes area (Husar *et al.*, 1981). Thus, future trends in visibility, even into the most northerly park sites, will depend on the emission control practices throughout the Midwest, but particularly of the large SO₂ sources.

ACIDIC DEPOSITION

The chemistry of precipitation throughout eastern North America appears to have been changed significantly over the past half-century in association with increased concentrations of sulphuric and nitric acids in the lower atmosphere (Likens, 1976; Galloway & Cowling, 1978; Glass & Loucks, 1980). Current levels of acidity in precipitation in the Great Lakes region are strongly acidic in the east (Fig. 4)—a condition which has raised concern about effects upon the integrity of aquatic and terrestrial resources (Stottlemeyer, 1982).

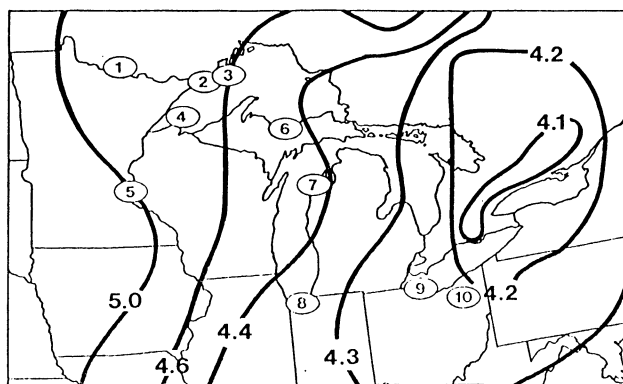


FIG. 4. Weighted averages of precipitation pH for the period April 1979 through March 1980. Data from the National Atmospheric Deposition Program. The scale is approximately 1 cm to 240 km.

Within eastern North America, there are large areas in which the surficial soil material and bedrock types are identified as 'potentially sensitive', because they have little ability to neutralize acids (Galloway & Cowling, 1978). Effects of acidic deposition on watersheds and aquatic resources are most likely to be expressed in areas where inputs of acid cannot be neutralized or buffered by constituents in the soils and water, and the pH of surface waters is depressed accordingly. Extinctions of fish populations have been reported in several areas (Harvey *et al.*, 1981). A question that is still under investigation concerns whether the alterations in water chemistry observed to date represent a time-trend (suggesting that many more lakes will be affected in the future than at present), or a steady-state of present acidic inputs and weathering rates, suggesting little further increase in the extent of damage even if current acid deposition continues.

Many changes in aquatic life have been linked to the alteration of surface waters by acid inputs. Causal relationships are being linked with depression in pH for some species, but with aluminium toxicity for others. In general, the observed changes in biota have been correlated with changes in pH, but causal effects have not been proven. Acidification has been accompanied by decreases in species diversity, changes in species dominance (Harvey *et al.*, 1981), changes in composition of

plankton communities and, therefore, the general structure of aquatic food-chains.

Experimental studies also indicate that many kinds of direct acid deposition effects are possible in terrestrial systems. These range from damage to leaf surfaces to leaching of essential nutrients from soils. Acid rain impacts on sensitive watersheds also appear frequently as reactions by the biota to the mobilization of soil aluminium. The solubility of this metal increases sharply with brief periods of high acidity from atmospheric inputs. Excess aluminium can affect cell division in roots, causing inhibition of root growth and phosphorus deficiency symptoms. Mortality of forest stands in Germany subjected to acid deposition (Ulrich *et al.*, 1980) has been attributed to toxic concentrations of aluminium. Inhibition of forest growth on poorly-buffered soils in the northeastern US could also occur if elevated acidic inputs continue. The significance of these processes for acid-sensitive ecosystems in the Great Lakes region has not yet been established, however (Glass & Loucks, 1980).

Recently-documented surveys of water quality in sensitive areas of northern Minnesota and Wisconsin show cause for concern in the area stretching from northern Minnesota to northern Michigan—including Voyageurs National Park, Grand Portage National Monument, the St Croix National Scenic Riverway, Isle Royale National Park, and Pictured Rocks National Lakeshore (Loucks *et al.*, 1982; Stottlemeyer, 1982). Results presented by Glass (1980) show an appreciable depression of stream pH during the snow-melt period in northern Minnesota, and similar responses are reported in Wisconsin (*Ibid.*).

OVERVIEW OF AIR POLLUTION THREATS TO THE NATIONAL PARK SITES

From the evidence on pollutant load and dose/response relationships summarized here, susceptibility of the ten parks etc. to pollution-induced alterations are seen to be governed by two main factors: the quality and abundance of susceptible resources (soils, water, or vegetation), and the loading rates (emissions or deposition) of the various pollutants that are suspected of causing changes. Alteration of the 'vista qualities' (i.e. visual amenities) along the Great Lakes shorelines (cf. Figs 1 and 3) probably ranks as the most dramatic alteration, and further degradation is possible. Sensitivity to photochemical oxidants in Voyageurs and Isle Royale National Parks may not be a serious problem, because O₃ concentrations may fall short of the exposures known to cause significant effects; but premature loss of coniferous foliage is widespread in these northern areas.

In addition, sulphate particles are being transported to the region, thus affecting visibility and raising the possibility of acid-alteration of susceptible lakes. The presence of somewhat acidic deposition for the past 15 years suggests that resource impacts could already be under way. In the southern and eastern portions of the region, significant impacts from primary emissions as well as transported pollutants are to be expected and are being observed qualitatively. At the same time, the

greatest reductions in visibility have taken place where the largest number of park users are present (Fig. 3).

The actual and potential pollutant threats are summarized in a presence/absence form in Table V. Estimates of probable effects will be subject to change as new research findings emerge, new methods are adopted, and new counter-measures are undertaken. The eventual time-trends in primary emissions in and around the region (residential, industrial, and transportation-related) are certain to influence prospective pollutant concentrations and their impacts. However, the direction and magnitude of changes in pollutant loadings over the next 20 years are quite uncertain at the present time. If current concentrations and deposition patterns are maintained over the next two decades, however, resource values will surely diminish and impacts seem likely to become noticeable to most National Park etc. users.

Steps to alleviate air pollution impacts have been a national goal of clean-air legislation in the US for more than 10 years. As noted earlier, however, control to date has focused on local problems, and pollutant loads transported over long distances remain relatively unchanged. Amendments to strengthen air-quality protection are being considered in the US Congress, but the needed controls will be difficult to implement and relatively costly (US/Canada, 1979). A wide range of benefits for a large part of the US accrue from the proposed controls, however, and protection of the natural resources and scenic vistas of National Parks etc. in the Great Lakes region is one of the significant benefits.

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SUMMARY

The Great Lakes region of the interior of North America supports a large human population, a major industrial base, and recreational and scenic amenities of unusual contrast and quality. To protect portions of this landscape and meet national recreational needs, the US Federal Government has established 10 National Parks, Monuments, and Lakeshores, in the region, extending from northern Minnesota to the southern shore of Lake Erie. However, air pollutant sources from the industrial Midwest, and large-scale coal combustion for electricity along the Ohio Valley, show evidence of significantly threatening the resource qualities protected in these parks.

A review of the natural resources and amenities in each of the National Parks, Monuments, and Lakeshores, in the region shows that scenic vistas are of primary significance, with unique biota (largely northern coniferous species and associated bird-life) and clear water also prominent. Pollutant concentrations in the southern sites, however, are above the thresholds that are known to produce stress, foliage damage, and altered growth-rates on many sensitive species, including the coniferous trees. These pollutants include gases such as sulphur dioxide and nitrogen oxides (NO_x) that are primary emissions of relatively local origin, as well as pollutants such as sulphate particulates, ozone, and acidic deposition, produced by chemical transformations during long-distance atmospheric transport. The particulates, in combination with the high average summer humidity, produce a reduction of visibility at the southern sites, and hence the partial loss of an important amenity.

TABLE V

Actual and Potential Air-pollution-induced Threats to Great Lakes National Parks, etc.

Park etc.	Major Natural Resources	Sources of Threat			
		SO ₂ Vegetation Effects	O ₃ Vegetation Effects	Visibility Reduction	Acid Deposition Aquatic Effects
1. Voyageurs National Park	Forests, lakes, streams		+	+	+
2. Grand Portage Nat. Mon.	Forests, streams, vistas		+	+	+
3. Isle Royale Nat. Park	Forests, wildlife, streams, vistas		+	+	+
4. Apostle Isls Nat. Lakeshore	Forests, shorelines, vistas		+	+	+
5. St Croix Nat. Scenic Riverway	Forests, streams, gorges, wildlife		+	+	+
6. Pictured Rocks Nat. Lakeshore	Forests, beach, outcrops, vistas		+	+	+
7. Sleeping Bear Dunes N.L.	Beaches, vegetation, vistas		+	++	
8. Indiana Dunes N.L.	Beaches, vegetation, wildlife	++	++	++	
9. Perry's Victory Nat. Mon.	Historical values, vistas			++	
10. Cuyahoga Valley NRA	Vegetation, topography, vistas	++	++	++	

+ indicates significant potential for future effects in the next two decades unless major reductions in pollutant loadings occur.
++ indicates that resource alterations are probably occurring now for specific pollutants indicated.

The northern and northwestern sites in Minnesota, Wisconsin, and the Upper Peninsula of Michigan, are not experiencing significant concentrations of primary-emission air pollutants, but those formed during long-distance transport—ozone, sulphate particulates, and acidic deposition—are being observed at elevated levels. Results include premature loss of foliage from the most sensitive species, somewhat reduced visibility during sulphate episodes, and moderate alteration of water quality in the most sensitive streams and lakes during spring snow-melt periods. Control of these pollutants, particularly those originating from relatively remote sources, would represent a substantial economic burden for the US, but these costs are being evaluated in relation to many other public benefits from controls in the region as the US Congress considers amendments to clean-air legislation. Protection and rehabilitation of the natural resources and amenities in the US National Parks etc. of the Great Lakes region, represent an additional important consideration in this debate.

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