RANKING WILDERNESS AREAS FOR SENSITIVITIES

AND RISKS TO AIR POLLUTION

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ABSTRACT: Wilderness areas may be compared for sensitivity to air pollutants by ranking the sum of the numbers of plant species sensitive to SO_2 and O_3, and weighted by the relative abundances of each species used in the summation. This ranking can be coupled with actual ambient air quality data for each wilderness area using a geographic information data base to determine the ranking of the wilderness area most at risk to air pollution. Using these procedures, the National Park Service has determined that out of 11 parks for which there is adequate data, Saguaro National Monument, Great Smoky Mountains, Shenandoah, and Rocky Mountain National Parks are experiencing the greatest risk of air pollution damage to vegetation from O_3 and SO_2 occurring simultaneously.

INTRODUCTION

If wilderness areas are exposed to air pollutants and acidic precipitation, the resources that are directly affected and which we are most concerned about are biological organisms. Plants and animals are directly affected through gas exchange mechanisms and surface deposition. Research on air pollution effects on vegetation has been performed for at least 100 years and has clearly established that plants are on average an order of magnitude more sensitive to SO_2 and O_3 than animals. It appears reasonable to conclude that studying the vegetation of wilderness areas would be a good approach to assessing the sensitivities of wilderness areas overall.

Why do we want to assess the sensitivities of wilderness areas? Federal land managers of these areas are faced with decisions to be made almost daily regarding issues and actions that may affect wilderness resources. Permits for new sources of pollution near the areas, changes in state air quality plans, and power plant expansions are just a few examples of such actions. In addition, the allocation of limited funds to projects must be guided by where the greatest needs are. All these activities would benefit from knowledge of which wilderness areas are most sensitive and most exposed to air pollutants. The approach described herein provides a methodology for generating this kind of information.

Certain wilderness areas are designated Class I under the Clean Air Act for protection against significant deterioration of air quality. The National Park Service (NPS) is responsible for 48 of these Class I areas (not all of which are officially designated wilderness areas) (table 1). Since all of these areas contain prime examples of major ecosystems, it became important to determine which were the most sensitive to O_3 and SO_2, the most phytotoxic air pollutants prevalent today. The method chosen was modeled after that used by Klopatek and others (1981) for ranking Forest Service RARE II tracts.

METHODS

Data Sources

Plant species and abundances.--The definition of dominant and common vascular plants used in this study is all trees and tree-sized shrubs, plus other shrubs and grasses that are significant within their habitats in the parks. Although this definition is not strict, its purpose was to ensure that the most widespread and commonly occurring vascular species were included in the analysis; no more rigorous definition is implied. The tree and large-shrub species were identified by the NPFLORA Data Base (Bennett 1982). Nonarboreal species names (shrubs, grasses, and forbs) were obtained from park naturalists, botanists, and other scientists most familiar with the flora of each park. These scientists were also requested to identiy species that in their opinion met the criteria of importance or significance within the park habitats and to estimate each species abundance in the park. Park superintendents were asked to request appropriate staff to rank species abundances as common, intermediate, or rare. These abundances are based primarily on their distribution within their common habitats, but also relative to all other species. Species lists and abundances compiled for each park are available in Esserlieu and Olson (1985). For this study the number

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Table 1.--Air quality Class I parks, locations and areas

Park	State	Park area in hectares
Acadia National Park	Maine	15,634
Arches National Park	Utah	22,035
Badlands National Park	South Dakota	26,001
Bandelier National Monument	New Mexico	9,416
Big Bend National Park	Texas	216,062
Black Canyon National Monument	Colorado	4,524
Bryce Canyon National Park	Utah	8,709
Canyonlands National Park	Utah	105,279
Capitol Reef National Park	Utah	72,728
Carlsbad Caverns National Park	New Mexico	12,282
Chiricahua National Monument	Arizona	3,820
Crater Lake National Park	Oregon	49,534
Craters of the Moon National Monument	Idaho	17,500
Denali National Park and Preserve	Alaska	784,885
Everglades National Park	Florida	557,819
Glacier National Park	Montana	375,366
Grand Canyon National Park	Arizona	493,059
Grand Teton National Park	Wyoming	46,865
Great Sand Dunes National Monument	Colorado	13,537
Great Smoky Mountains National Park	North Carolina/Tennessee	158,030
Guadalupe Mountains National Park	Texas	18,960
Haleakala National Park	Hawaii	7,798
Hawaii Volcanoes National Park	Hawaii	49,817
Isle Royale National Park	Michigan	53,370
Joshua Tree National Monument	California	173,889
Lassen Volcanic National Park	California	31,963
Lava Beds National Monument	California	23,035
Mammoth Cave National Park	Kentucky	21,095
Mesa Verde National Park	Colorado	3,278
Mount Rainier National Park	Washington	85,267
North Cascades National Park	Washington	213,128
Olympic National Park	Washington	348,895
Petrified Forest National Park	Arizona	20,339
Pinnacles National Monument	California	5,241
Point Reyes National Seashore	California	10,267
Redwood National Park	California	44,121
Rocky Mountain National Park	Colorado	97,058
Saguaro National Monument	Arizona	28,895
Sequoia-Kings Canyon National Parks	California	303,793
Shenandoah National Park	Virginia	31,978
Theodore Roosevelt National Park	North Dakota	11,774
Virgin Islands National Park	Virgin Islands	5,952
Voyageurs National Park	Minnesota	88,678
Wind Cave National Park	South Dakota	11,449
Yellowstone National Park	Idaho/Montana/Wyoming	1,251,676
Yosemite National Park	California	261,427
Zion National Park	Utah	48,813

of species ranged between 148 in Great Smoky Mountains to nine in Petrified Forest. This large variation represents differences primarily in park species diversities, but also in individual interpretaions by park staffs and in completeness of the parks' floras. Overall, 940 different species were included in this study (table 2).

Sensitivities of natural vegetation.--Data sources presenting original research results as well as those comparing results of other researchers were combined to determine species sensitivities to SO_2 and O_3. A compilation of open literature sources from the NPS provided most of the references (Bennett, personal communication). In general, these sensitivities were based on laboratory and field experiments with visible foliar injury as the measured parameter. Although visible injury is not always associated with growth reductions, it has been the most commonly reported test result. Nearly one-third of the 940 selected species occurring in the parks have been tested for tolerance to either SO_2 or O_3 or both pollutants (table 2). Sensitivity classifications were "sensitive", "intermediate", "resistant", and "unknown"

Table 2.--Numbers of species used to determine vulnerabilities of each park by pollutant

Park	Vascular Plant Species: SO_2 Sensitivity Studied	O_3 Sensitivity Studied	Total Used in Study	Lichens: SO_2 Sensitivity studied	Total Used in Study
Acadia	38	20	59	44	136
Arches	34	10	77	1	12
Badlands	22	9	42	*	*
Bandelier	40	16	83	*	*
Big Bend	27	8	135	27	201
Black Canyon	16	7	17	*	*
Bryce Canyon	35	11	60	*	*
Canyonlands	41	14	88	*	*
Capitol Reef	16	5	26	*	*
Carlsbad Caverns	17	7	54	*	*
Chiricahua	15	5	39	6	192
Crater Lake	15	9	35	5	41
Craters of the Moon	8	4	10	*	*
Denali	8	5	30	*	*
Everglades	6	3	110	*	35
Glacier	38	13	64	10	89
Grand Canyon	31	10	63	14	87
Grand Teton	18	8	29	1	17
Great Sand Dunes	28	11	53	3	8
Great Smoky Mountains	67	42	148	43	301
Guadalupe Mountains	23	9	63	*	*
Isle Royale	20	12	31	97	489
Joshua Tree	8	0	56	*	*
Lassen Volcanic	20	10	33	*	*
Lava Beds	25	12	42	*	*
Mammoth Cave	49	37	118	*	*
Mesa Verde	26	9	46	13	45
Mount Rainier	18	5	35	15	132
North Cascades	38	11	55	2	34
Olympic	22	5	37	26	172
Petrified Forest	4	0	9	*	*
Pinnacles	2	1	15	*	*
Point Reyes	11	5	35	*	*
Redwood	16	6	39	13	32
Rocky Mountain	19	7	38	28	348
Saguaro	19	7	61	*	*
Sequoia-Kings Canyon	31	14	96	26	73
Shenandoah	65	44	132	35	189
Theodore Roosevelt	14	7	21	36	208
Voyageurs	25	17	35	75	404
Wind Cave	24	11	46	6	35
Yellowstone	15	5	23	6	49
Yosemite	17	13	34	5	57
Zion	35	13	64	24	168

Indicates numbers of species for which sensitivity was known and total species in the data sets for vascular species and lichens used in this study. Asterisks in the lichen columns indicated the lichen flora is virtually unknown.

and were estimated from reported experimental results. The master list of species sensitivities and references appears in Esserlieu and Olson (1985). When references conflicted over the sensitivity rating, preference was shown for more recent studies and chronic exposure levels. If neither criteria pertained, then the more sensitive classification was used. Erring in favor of the resource was preferred to understating sensitivity.

Sensitivities of lichens.--The sensitivities of lichens to SO_2 was also used as an indicator of the vulnerability of Class I parks. Wetmore (1983) reported on lichen species found in 42 of the Class I parks and their estimated sensitivities to SO_2. For this study, the lichen species found in the parks were summarized according to: (1) Wetmore's five SO_2 sensitivity classifications; (2) different species known to occur in a park; (3) completeness of lichens surveys; and (4) the number of type locales for specimens originally described from that park. The five SO_2 sensitivity classifications (sensitive, sensitive to intermediate, intermediate, intermediate to resistant, and resistant) are based on literature reports of laboratory experiments and field observations. Lichen species data pertain to the area within park boundaries except for the North Casades National Park, which is characterized by data for immediately adjacent lands.

Sulfur dioxide data.--In this study, air quality data for SO_2 are based on monitoring data from the U.S. Environmental Protection Agency (EPA) for the years 1977 to 1982. Sulfur dioxide data are from monitors within 50 and 100 km of the park centroid because dispersion from tall stacks and certain atmospheric conditions may result in elevated SO_2 levels at these distances. The average annual arithmetic mean values in micrograms per cubic meter (ug/m^3) are reported in table 3. The only station to report

Table 3.--Air quality data for SO_2 and O_3 for 44 Class I National Parks

	Park	SO_2 Annual Average 50 km	SO_2 Annual Average 100 km	O_3 7-mo 7-h Average
		(Micrograms per cubic meter)		
1	Acadia	3.59	22.59	71.2
2	Arches	0.00	4.29	*
3	Badlands	0.00	2.96	84.5
4	Bandelier	0.00	6.65	92.6
5	Big Bend	*	*	75.7
6	Black Canyon	*	*	*
7	Bryce Canyon	0.00	8.99	97.5
8	Canyonlands	0.00	4.29	98.1
9	Capitol Reef	*	*	97.9
10	Carlsbad Caverns	0.00	11.24	82.4
11	Chiricahua	0.00	53.58	100.4
12	Crater Lake	0.00	13.09	63.1
13	Craters of the Moon	*	*	96.5
14	Denali	*	*	*
15	Everglades	3.77	7.24	*
16	Glacier	2.65	0.00	*
17	Grand Canyon	8.29	0.00	92.2
18	Grand Teton	*	*	*
19	Great Sand Dunes	*	*	96.9
20	Great Smoky Mountains	13.98	32.07	91.2
21	Guadalupe Mountains	*	*	82.4
22	Isle Royale	*	*	*
23	Joshua Tree	2.74	4.23	103.3
24	Lassen Volcanic	*	*	96.3
25	Lava Beds	0.00	13.09	56.7
26	Mammoth Cave	5.73	32.53	78.8
27	Mesa Verde	0.00	24.41	*
28	Mount Rainier	0.00	41.03	51.0
29	North Cascades	*	*	50.4
30	Olympic	62.15	41.03	50.8
31	Petrified Forest	*	*	101.6
32	Pinnacles	3.09	0.00	84.3
33	Point Reyes	5.49	12.56	77.7
34	Redwood	*	*	55.1
35	Rocky Mountain	0.00	33.92	85.7
36	Saguaro	9.96	88.80	100.0
37	Sequoia-Kings Canyon	*	*	109.0
38	Shenandoah	0.00	40.23	87.1
39	Theodore Roosevelt	2.86	3.88	*
40	Voyageurs	3.55	3.95	*
41	Wind Cave	2.50	2.96	84.5
42	Yellowstone	0.00	2.50	*
43	Yosemite	*	*	101.0
44	Zion	8.99	0.00	97.5

All SO_2 data are for 1977-1982 and O_3 data are for 1980. Asterisks indicate no data available. Park numbers are used in figures 4 - 11.

exceedances of the National Ambient Air Quality Standard of 80 ug/m^3 annual average for SO_2 was Tucson, AZ, 9 km from Saguaro National Monument, in 1980 and 1981. Values of more than 30 ug/m^3 were reported from stations 42 to 81 km from eight parks: Chiricahua, Creat Smoky Mountains, Mammoth Cave, Mount Rainier, Olympic, Rocky Mountain, Saguaro, and Shenandoah.

Ozone data.--The ozone values are 7-hour daylight mean concentrations in micrograms per cubic meter (ug/m^3) for the seven-month period, April through October, 1980 (table 3). Ozone data were obtained from the EPA SAROAD (Storage and Retrieval of Aerometric Data) data base. Stations were selected to minimize the influence of high readings associated with urban areas; approximately 360 stations had appropriate data for 1980. Daily averages were calculated as the average concentration between the hours of 0900 and 1600 local standard time. The statistical technique of "kriging" was employed to estimate grid values from the irregularly spaced monitoring stations. Ozone values were not estimated for points that did not have data from at least five monitoring stations within 500 km or one station within 30 km. Values for each park were estimated for the half-degree cell in which the park centroid fell.

Ranking Methods

Selected plant species for each park were used to assess potential sensitivity and actual risk. Data were collected, sensitivity ratings were tabulated for each of these species for each park, abundances of the species were estimated, and parks were ranked based on combinations of these data. The three Class I tropical parks outside the conterminous United States (Haleakala, Hawaii Volcanoes, and Virgin Islands) were not analyzed because of inadequate knowledge of their floras and their sensitivities to air pollution. Sequoia and Kings Canyon National Parks, which are adjacent and have similar floras, are treated as one park for this study. Thus a total of 44 parks were used in this analysis.

Limitations of data and method.--Although the best data available were used, limitations of the analysis should be recognized. First, definitions of sensitivities of species vary with testing methods and the researcher's individual assessments. Second, knowledge about species sensitivities in the parks varies substantially. For some parks, sensitivities of a very small percentage of species have been tested, but for others a large portion of species have been tested. Table 2 compares the numbers of species studied for air pollution sensitivity with the total number of species for each park used in this study. The ranking method used in this study considers only the sensitivities of species whose responses have been tested; the ratio of species with known sensitivities to the total number in the park is used only to define reliability, but is not used in the ranking itself. A third limitation is the lack of lichen data for all parks. Although 44 parks are ranked based on sensitivity of vascular plant species, only 25 parks are ranked based on sensitivity of lichen species. In calculating overall ranks, only 22 parks had data for more than three species of lichens.

Approach.--Several types of rankings were performed which determined the relative potential sensitivities of the parks, and the parks most at risk from detrimental impacts of air pollution. Each ranking combined species sensitivities and relative abundances to produce overall values. The values are produced by weighting common, intermediate, and rare species (3, 2, and 1, respectively, 1 for unknown abundances), and similarly weighting sensitive, intermediate, and resistant species (3, 2, and 1, respectively, 0 if unknown). Thus, common sensitive species were given the greatest weight in this analysis. These sensitivity and abundance values were multiplied, summed for all species in the park, then divided by the total number of species for which sensitivities are known to determine the sensitivity value of a park (see Equation 1). If a species sensitivity was unknown, that species did not contribute to the summation. This step was repeated for each pollutant and for lichens and all three were summed to produce an overall value of park vegetation sensitivity. The value will hereafter be referred to as vulnerability since it combines sensitivities and abundances.

$$V_p = \frac{\sum_{x=1}^{n} S_x A_x}{k} + \frac{\sum_{y=1}^{n} O_y A_y}{l} + \frac{\sum_{z=1}^{n} l_z}{m} \qquad (1)$$

$$(V_p = V_{SO_2} + V_{O_3} + V_l)$$

where: V_p = vulnerability of a park;
S = SO_2 sensitivity of a vascular species (0-3);
O = ozone sensitivity of a vascular species (0-3);
A = abundance of a vascular species (1-3);
L,l = lichen SO_2 sensitivity (0-3);
n = number of species in the park;
k,l = number of vascular plants for which SO_2 or O_3 sensitivity is known; and
m = number of lichen species for which SO_2 sensitivity is known.

When lichen sensitivities were unknown or not available, the V_p value was not calculated. The vulnerabilities were then ranked from low to high and assigned sequential numbers from 1 to 44 or 25 depending on the analysis. The data that are presented are these pure rank values and not the actual vulnerability values themselves. The lowest number values represent the most vulnerable parks.

The final stage in the analysis consisted of coupling the sensitivity ranks of the parks with the ambient air quality data. By comparing the parks that were most sensitive with the air pollutant concentrations, the parks that were most at risk to air pollution effects could be identified.

RESULTS

Vulnerabilities of Parks

Data on park vegetation vulnerabilities to air pollution are of interest individually, but are also valuable for management purposes when they indicate one park's tolerance relative to another's. These data allow only for qualitative and comparative rankings between parks in this study. Since the original data vary significantly in quality and completeness, even these relative ranks should be used cautiously. Nevertheless, estimates of relative vulnerabilities of the parks are useful. Although numeric values are assigned for purposes of ranking, no quantitative significance is implied or inferred, and none should be assumed. No absolute importance should be assigned to the position of one park relative to another. We recommend comparing park vulnerabilities roughly in groups of four or more.

Summary of park ranks.--An overall summary of park ranks appears in table 4. This table summarizes potential vulnerabilities only and

Table 4.--Ranks of park vulnerabilities based on values calculated in Equation 1

Park	Vascular Plants SO_2	Vascular Plants O_3	Vascular Plants $SO_2 + O_3$	Lichens	Vascular Plants + Lichens
Acadia	11.0	19.0	14	7	2
Arches	34.0	38.0	39	17	19
Badlands	39.0	25.5	35	*	*
Bandelier	37.0	28.0	32	*	*
Big Bend	41.0	42.0	43	13	23
Black Canyon	24.0	13.0	17	*	*
Bryce Canyon	40.0	30.5	38	*	*
Canyonlands	21.0	35.0	25	*	*
Capitol Reef	31.0	24.0	24	*	*
Carlsbad Caverns	30.0	29.0	26	*	*
Chiricahua	23.0	36.0	28	15	16
Crater Lake	27.5	17.0	20	3	14
Craters of the Moon	26.0	12.0	18	*	*
Denali	2.0	6.5	3	*	*
Everglades	43.0	33.5	41	*	*
Glacier	8.0	11.0	10	14	3
Grand Canyon	17.0	8.5	11	9	8
Grand Teton	19.0	14.0	12	25	20
Great Sand Dunes	42.0	37.0	42	17	24
Great Smoky Mountains	20.0	15.0	15	5	7
Guadalupe Mountains	36.0	25.5	30	*	*
Isle Royale	4.0	8.5	5	10	1
Joshua Tree	5.0	*[1]	37	*	*
Lassen Volcanic	12.5	6.5	9	*	*
Lava Beds	33.0	32.0	33	*	*
Mammoth Cave	1.0	3.0	1	*	*
Mesa Verde	44.0	39.0	44	22	25
Mount Rainier	38.0	27.0	34	2	21
North Cascades	32.0	30.5	31	23	22
Olympic	29.0	23.0	23	4	15
Petrified Forest	25.0	*[1]	40	*	*
Pinnacles	12.5	40.5	27	*	*
Point Reyes	15.0	40.5	29	*	*
Redwood	35.0	33.5	36	8	18
Rocky Mountain	7.0	1.0	4	19	5
Saguaro	3.0	2.0	2	*	*
Sequoia-Kings Canyon	14.0	5.0	8	12	6
Shenandoah	22.0	22.0	21	6	12
Theodore Roosevelt	6.0	10.0	7	17	4
Voyageurs	18.0	20.0	19	11	9
Wind Cave	10.0	21.0	16	24	17
Yellowstone	27.5	18.0	22	1	10
Yosemite	9.0	4.0	6	21	11
Zion	16.0	16.0	13	20	13

[1]No ozone response data available.

is not related in any way to ambient air pollution concentrations. Parks that had the same vulnerabilities were given the same ranks using an averaging algorithm.

Ten most and least vulnerable parks.--For discussion purposes it is easier to shorten the ranking lists to the ten most and least vulnerable parks, shown in table 5. Each column in this table corresponds to the same column in the previous table, but lists the ten most vulnerable in descending order and the ten least vulnerable in ascending order. The first three columns are based on 44 parks in the analysis and the last two columns are based on 25 parks.

Vulnerability based on vascular plant sensitivities to SO_2.--Parks that are most vulnerable to SO_2 are quite varied and geographically dispersed from the eastern U.S. to Alaska. The most sensitive are Mammoth Cave, Denali, Saguaro, and Isle Royale. The least sensitive parks are equally diverse and include Mesa Verde, Everglades, Great Sand Dunes, and Big Bend. Seven out of ten of the least sensitive parks are primarily arid desert type ecosystems.

Vulnerability based on vascular plant sensitivities to O_3.--Because the sensitivities of natural vegetation to O_3 are less well known than for SO_2, the O_3 vulnerability of parks is based on less data. For two parks, Joshua Tree and Petrified Forest, no data on plant sensitivities to O_3 were available. Contrary to expectations, most of the parks in the top ten are in the western U.S., and only two parks, Isle Royale and Mammoth Cave, are in the eastern U.S. The O_3 vulnerabilities of Acadia, Shenandoah, and Great Smoky Mountain can be seen in table 4. With one exception (Everglades), most of the parks in the least vulnerable top ten are in the western U.S.

Vulnerability based on vascular plant sensitivities to SO_2 and O_3.--The twenty parks most and least vulnerable to both pollutants are very similar to those vulnerable to SO_2 alone, indicating the predominance of sensitivity to this pollutant in the analysis. Mammoth Cave, Saguaro, Denali, Rocky Mountain, and Isle Royale are the most vulnerable parks to SO_2 and O_3 combined, while Mesa Verde, Big Bend, Everglades, and Great Sand Dunes are the least vulnerable.

Table 5.--Twenty most and least air pollutant vulnerable National Parks

	Vascular Plants			Lichens	
	SO_2	O_3	$SO_2 + O_3$	Alone	With Vascular Plants
MOST VULNERABLE PARKS IN DESCENDING ORDER					
Most	Mammoth Cave	Rocky Mountain	Mammoth Cave	Yellowstone	Isle Royale
	Denali	Saguaro	Saguaro	Mount Rainier	Acadia
	Saguaro	Mammoth Cave	Denali	Crater Lake	Glacier
	Isle Royale	Yosemite	Rocky Mountain	Olympic	Theo. Roosevelt
	Joshua Tree	Sequoia-Kings Cnyn.	Isle Royale	Gt. Smoky Mtns.	Rocky Mountain
	Theo. Roosevelt	Denali)	Yosemite	Shenandoah	Sequoia-Kings Cnyn.
	Rocky Mountain	Lassen Volcanic)	Theo. Roosevelt	Acadia	Gt. Smoky Mtns.
	Glacier	Isle Royale)	Sequoia-Kings Cnyn.	Redwood	Grand Canyon
	Yosemite	Grand Canyon)	Lassen Volcanic	Grand Canyon	Voyageurs
Least	Wind Cave	Theo. Roosevelt	Glacier	Isle Royale	Yellowstone
LEAST VULNERABLE PARKS IN ASCENDING ORDER					
Least	Mesa Verde	Big Bend	Mesa Verde	Grand Teton	Mesa Verde
	Everglades	Petrified Forest)	Big Bend	Wind Cave	Gt. Sand Dunes
	Gt. Sand Dunes	Pinnacles)	Gt. Sand Dunes	North Cascades	Big Bend
	Big Bend	Mesa Verde	Everglades	Mesa Verde	North Cascades
	Bryce Canyon	Arches	Petrified Forest	Yosemite	Mount Rainier
	Badlands	Gt. Sand Dunes	Arches	Zion	Grand Teton
	Mount Rainier	Chiricahua	Bryce Canyon	Rocky Mountain	Arches
	Bandelier	Canyonlands	Joshua Tree	Arches)	Redwood
	Guadalupe Mtns.	Redwood)	Redwood	Gt. Sand Dunes)	Wind Cave
Most	Redwood	Everglades)	Badlands	Theo. Roosevelt)	Chiricahua
BASED ON	44 PARKS			25 PARKS	

Brackets indicate parks with equal ranks.

Vulnerability based on lichen sensitivities to SO_2.--The parks most and least vulnerable based on lichen sensitivities to SO_2 are quite different from those vulnerable based on vascular plants, probably due to the fewer number of parks in the analysis. Only one park, Isle Royale, appears in both most vulnerable lists and two, Mesa Verde and Great Sand Dunes appear in both least vulnerable lists. The most and least vulnerable parks appear to be dominated again by western parks. In addition, two parks, Yellowstone and Grand Teton, which are adjacent to one another, came out most and least vulnerable respectively. This was due to the appearance of a common sensitive lichen in Yellowstone but not in Grand Teton, which is probably due to inadequate knowledge of the Grand Teton lichen flora and not the actual absence of the species from the park. This fluke in the analysis, in addition to it being based on only 25 parks, suggests that its usefulness is limited.

Vulnerability based on both vascular plant and lichen sensitivities.--This list of the top ten most vulnerable parks, which is the most inclusive of sensitive plants, is different from the list based just on vascular plants sensitive to SO_2 and O_3. Several parks, including Acadia, Great Smoky Mountains, Sequoia-Kings Canyon, and Glacier appear on the list. Mammoth Cave, however, does not because there is no published lichen flora yet for the park. Those parks least vulnerable, however, are very similar to those based on vascular plant sensitivies, indicating that vascular plant sensitivities determine park vulnerabilities when the species are quite tolerant.

Relationship between SO_2 and O_3 vulnerability ranks.-- A useful relationship to examine for cross-vulnerability would be the one between SO_2 and O_3 ranks. This is shown in figure 1 and illustrates that most parks are equally vulnerable to both pollutants. Parks are identified in this and all subsequent graphs by the numbers which are in column one in table 3. Eleven parks, Saguaro, Mammoth Cave, Rocky Mountain, Yosemite, Denali, Isle Royale, Glacier, Theodore Roosevelt, Lassen Volcanic, Sequoia-Kings Canyon, and Grand Canyon are all highly vulnerable to both pollutants. Four parks, however, depart somewhat from this relationship in that they are highly vulnerable to SO_2 but not to O_3: Joshua Tree, Pinnacles, Petrified Forest, and Point Reyes. No parks appeared to be highly vulnerable to O_3 alone and not SO_2.

Parks at Risk

Relationship between SO_2 and O_3 concentrations in parks.--Figure 2 shows a plot of the O_3 and 100 km SO_2 concentrations for the 22 parks that have such paired data. As expected, no significant correlation occurs between the two pollutants in this graph (nor with the 50 km

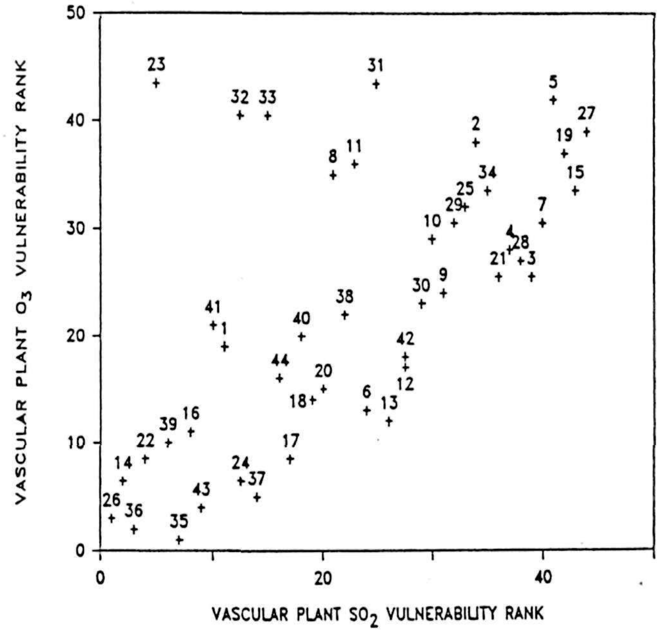

Figure 1.--Scattergram of SO_2 and O_3 vulnerability ranks of 44 national park units based on vegetation sensitivities. Park ranks are shown by their positions along the x and y axes. Numbers near each point (+ symbol) are park codes and are given in table 3.

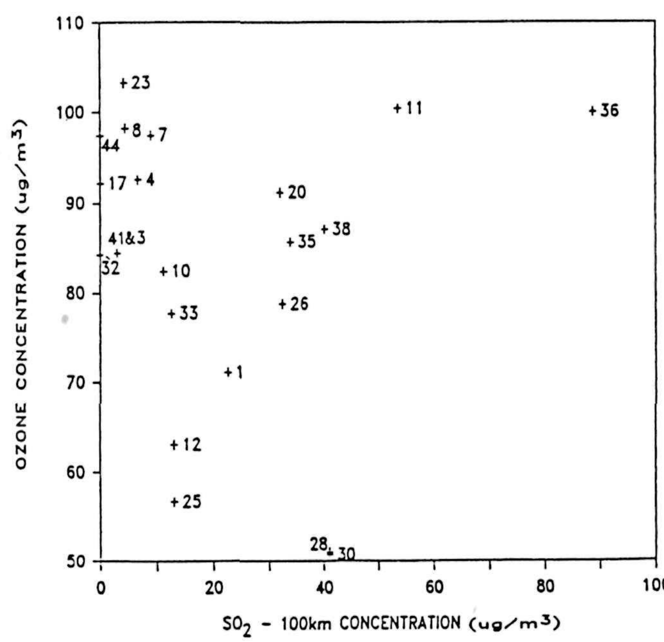

Figure 2.--Scattergram of measured SO_2 and O_3 concentrations at monitoring stations proximate to 22 national park units. Sources for these concentrations are given in the text. Parks not indicated on this figure did not have paired monitoring data to be included. Park codes are given in table 3.

SO_2 data). What we are interested in determining, however, is whether or not there are any parks with high values for both pollutants, i.e. parks that are located in the upper right portion of the graph. It is worth noting that about six parks are found in this area of the graph: Saguaro, Chiricahua, Shenandoah, Mammoth Cave, Great Smoky Mountains, and Rocky Mountain. The subsequent analysis will compare parks (with air pollution data) that are vulnerable and are experiencing high levels of pollutants.

Risk Assessment.--Assessment of parks at risk can be performed most easily using a graphical technique. By plotting the air quality concentration for each park against its respective sensitivity ranking a graph of parks at risk is generated. A schematic drawing of this plot is shown in figure 3. We call the entire plot the probability of injury occurring in national park units. Parks that are experiencing high pollutant concentrations and have high vulnerability rankings are probably experiencing current pollution effects, while those with low concentrations and vulnerability rankings may experience injury in the future. Each plot (analysis) is based on slightly different numbers of parks (75% to 25% of the total of 44) because of missing air pollution data (table 3). In general, the fewer parks in the analysis, the less useful it is. Seven such plots, roughly in order of decreasing number of parks, are presented below.

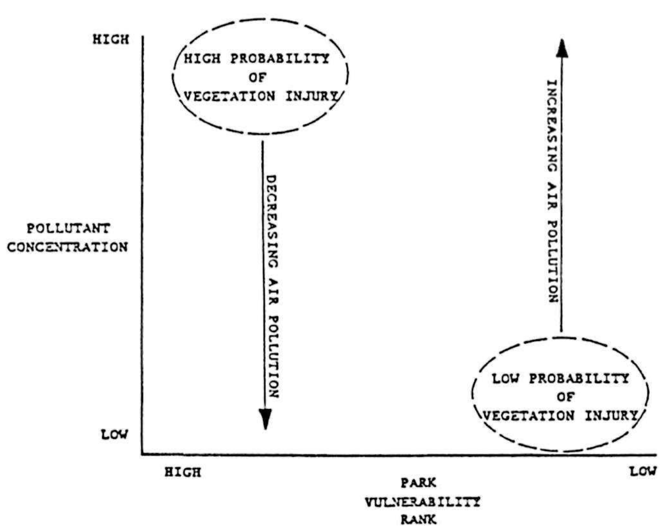

Figure 3.--Conceptual plot of probability of vegetation injury in national parks. Each park pollutant concentration is plotted against the parks vulnerability rank. Parks appearing in the lower right quadrant have low probabilities of vegetation injury while those in the upper left quadrant have high probabilities of vegetation injury. Parks appearing elsewhere in the plot have intermediate probabilities. As air pollution increases or decreases in a park, the probability of vegetation injury moves along the trajectories shown by the two arrows.

Vascular Plants - SO_2 - 50 km.--Twenty-nine parks have SO_2 data representing them to be included in this and the next analysis. Only one park, Olympic, appears to be near high SO_2 concentrations (>60 ug/m^3) (fig. 4). Since it has a low vulnerability rank, however, it probably has an intermediate chance of experiencing current injury. Parks with high vulnerabilities may be experiencing levels of SO_2 below 20 ug/m^3.

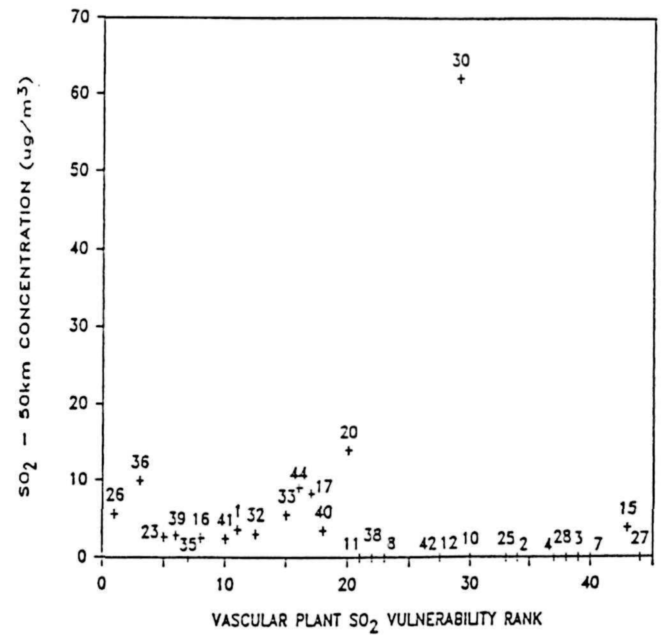

Figure 4.--Scattergram of measured SO_2 concentrations (ug/m^3) at monitoring stations within 50 km of 29 parks and park SO_2 vulnerability ranks based on SO_2 sensitivities of vascular plants. Park codes are given in table 3.

Vascular Plants - SO_2 - 100 km. Five parks, Saguaro, Shenandoah, Chiricahua, Olympic, and Mt. Rainier are potentially experiencing high SO_2 concentrations according to monitors at this distance (fig. 5), with the first three ranked in roughly the upper half of the vulnerability rankings. Those three parks may be experiencing current SO_2 plant injury. Six more parks, Mammoth Cave, Rocky Mountain, Acadia, Olympic, Mount Rainier, and Great Smoky Mountains, are potentially being exposed to SO_2 values >20 ug/m^3 and are highly ranked, suggesting they may experience SO_2 injury in the near future.

Vascular Plants - O_3.--Of the 33 parks included in this analysis, many more could be experiencing high concentrations of pollutant (O_3) than those in the SO_2 analysis (fig. 6). Eight parks, Saguaro, Yosemite, Sequoia-Kings Canyon, Lassen, Craters of the Moon, Great Smoky Mountains, Grand Canyon, and Zion could all be experiencing O_3 concentrations >90 ug/m^3 and are highly ranked, while Rocky Mountain, Mammoth Cave, Shenandoah, and Wind Cave are highly ranked (upper 50th percentile) and just below this value. Eight more parks are above this O_3 value but are ranked low in vulnerability.

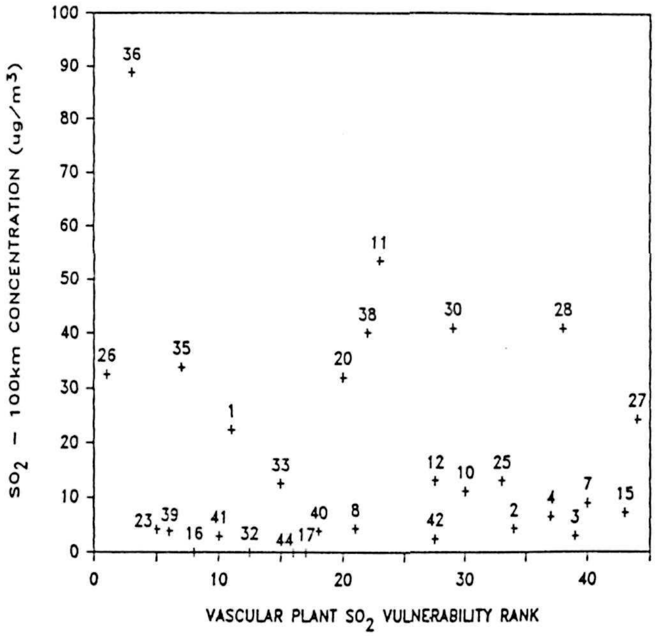

Figure 5.--Scattergram of measured SO_2 concentrations (ug/m^3) at monitoring stations within 100 km of 29 parks and park SO_2 vulnerability ranks based on SO_2 sensitivities of vascular plants. Park codes are given in table 3.

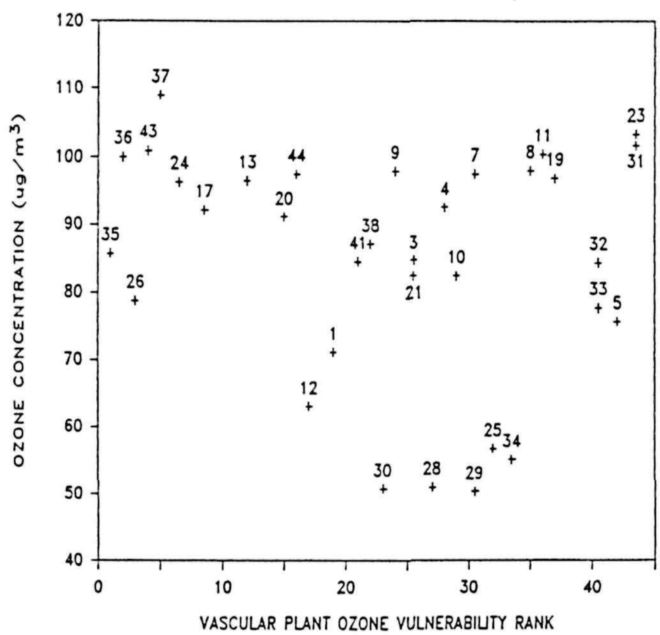

Figure 6.--Scattergram of measured O_3 concentrations (ug/m^3) at monitoring stations near 33 parks and park O_3 vulnerability ranks based on O_3 sensitivities of vascular plants. Park codes are given in table 3.

Vascular Plants - SO_2 + O_3. This assessment is shown with a pseudo-three-dimensional graph using different symbols for different levels of the third variable. In these two examples, one each for SO_2 at 50 and 100 km, SO_2 is the variable plotted with different symbols. Only 22 park units with both SO_2 and O_3 value are plotted. Parks with a high certainty of current injury would have to meet three criteria: high vulnerability rank, and both high SO_2 and O_3 values. Virtually no parks meet these criteria using the 50 km SO_2 values (Olympic has a low vulnerability rank) (fig. 7), but with the 100 km SO_2 data, Saguaro, Rocky Mountain, Great Smoky Mountains, Mammoth Cave, and Shenandoah do (fig. 8). These parks are probably experiencing the greatest injury on vascular plants currently from both SO_2 and O_3. Chiricahua appears to be near high SO_2 and O_3 monitoring stations, but has a low vulnerability rank.

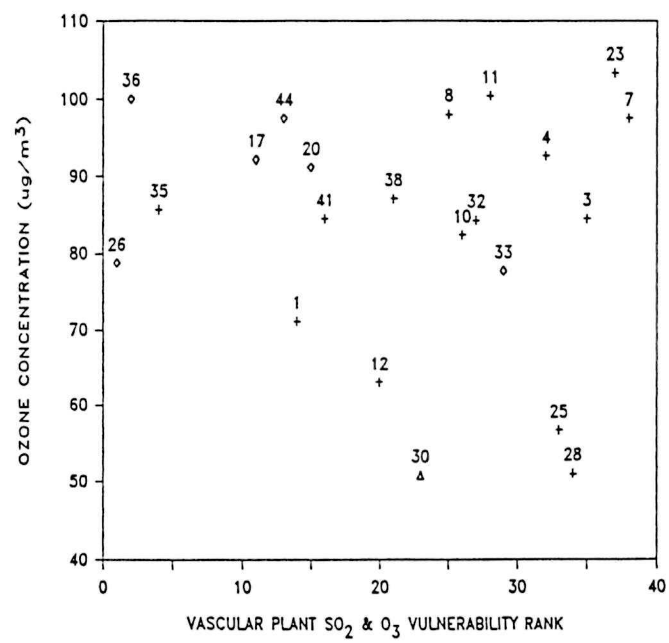

Figure 7.--Scattergram of measured O_3 concentrations and 50 km SO_2 concentrations (both in ug/m^3) for 22 parks and park vulnerability ranks based on combined SO_2 and O_3 sensitivities of vascular plants. Park codes are given in table 3. SO_2 values >16 ug/m^3 (> mean + + one standard deviation) are indicated by a triangle; values between 5 and 16 ug/m^3 (mean $\pm$ o standard deviation) by a diamond; and values <5 ug/m^3 (<mean - one standard deviation) by a plus symbol.

Lichens - SO_2 - 50 km. Using just lichens as indicators of SO_2 vulnerability, 17 parks qualified for risk analysis using SO_2 data. Olympic National Park shows extreme risk to current effects because it is high ranked and is experiencing high SO_2 values (fig. 9). Most other parks have low values using stations at this distance.

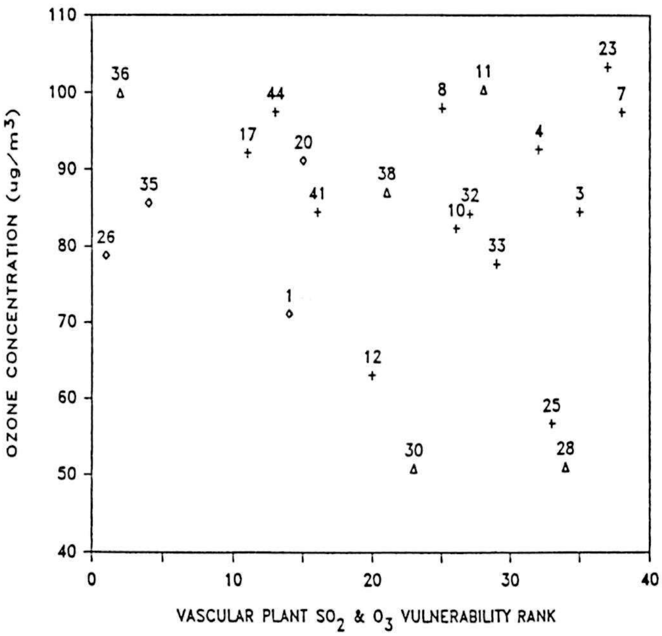

Figure 8.--Scattergram of measured O_3 concentrations and 100 km SO_2 concentrations (both in ug/m^3) for 22 parks and park vulnerability ranks based on combined SO_2 and O_3 sensitivities of vascular plants. Park codes are given in table 3. SO_2 values >38 ug/m^3 (> mean + one standard deviation) by a triangle; values between 18 and 38 ug/m^3 (mean $\pm$ one standard deviation) by a diamond; and values <18 ug/m^3 (<mean - one standard deviation) by a plus symbol.

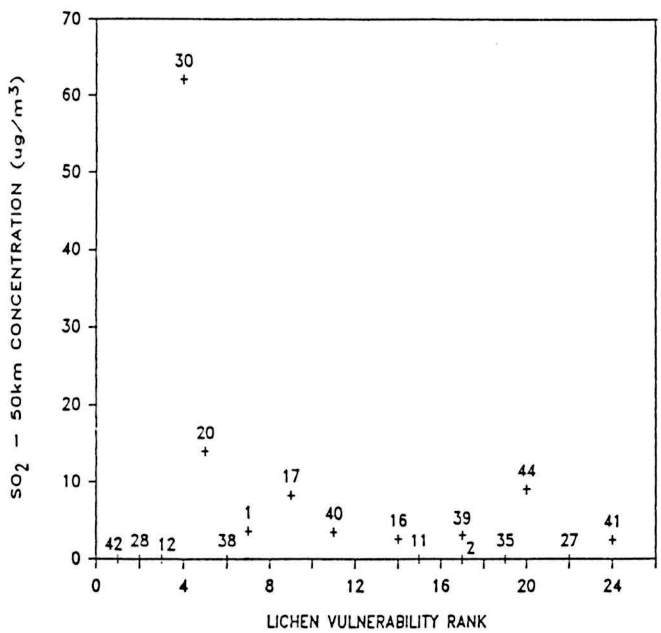

Figure 9.--Scattergram of measured SO_2 concentrations (ug/m^3) at monitoring stations within 50 km of 17 parks and park vulnerability ranks based on SO_2 sensitivities of lichens. Park codes are given in table 3.

Lichens - SO_2 - 100 km. Using stations within 100 km adds four more parks to the list of parks at risk to lichen effects: Mount Rainier, Shenandoah, Acadia and Great Smoky Mountains (fig. 10). Lichen effects due to SO_2 in these parks may occur at a later time than in Olympic due to more distant sources, as evidenced by additional monitoring stations between 50 and 100 km.

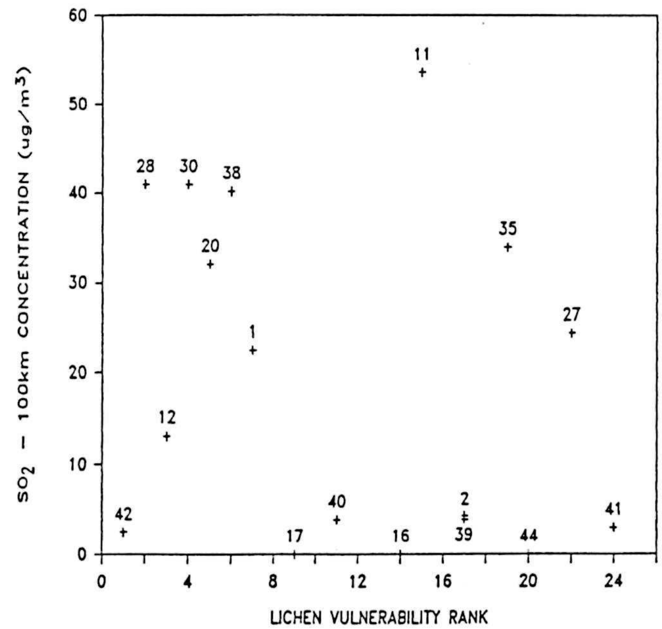

Figure 10.--Scattergram of measured SO_2 concentrations (ug/m^3) at monitoring stations within 100 km of 17 parks and park vulnerability ranks based on SO_2 sensitivities of lichens. Park codes are given in table 3.

Vascular Plants + Lichens - SO_2 + O_3. This may be considered the most important assessment since it includes vulnerabilities based on both vascular plants and lichens, and park units containing both SO_2 and O_3 values. However, out of the 44 class I parks in the study, only 11 parks have data to make the assessment (fig. 11). Thus the usefulness of this assessment is somewhat limited. Using the 100 km SO_2 values, Shenandoah, Great Smoky Mountains, Acadia, and Rocky Mountain appear to be most at risk to current effects on vascular plants and lichens from both SO_2 and O_3.

DISCUSSION

No study is worthwhile unless it can be validated in some fashion. In this particular study an easy way to test its validity is to verify if parks that are at high risk are actually experiencing air pollution injury to vegetation and conversely, if parks at low risk are not showing any injury. If a number of parks at low risk are showing some injury then it would suggest the analysis is faulty.

Parks that are currently experiencing foliar injury on vascular plant vegetation from O_3 include Mammoth Cave, Shenandoah, Great Smoky

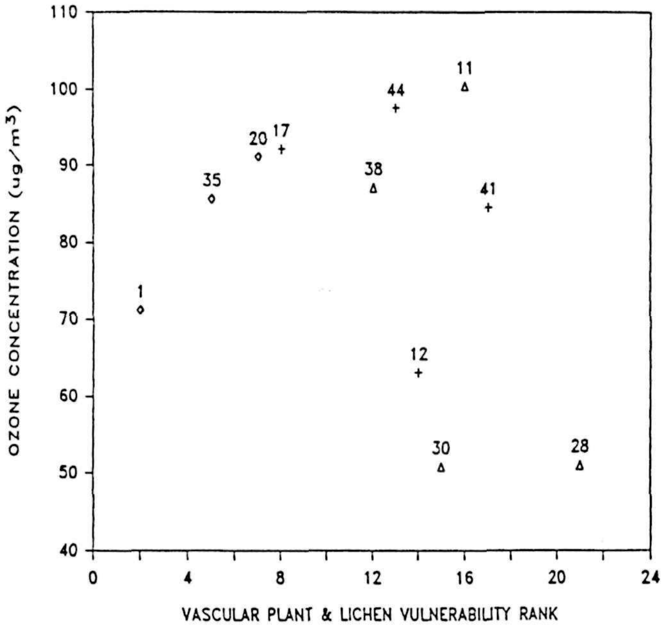

Figure 11.--Scattergram of measured O_3 concentrations and 100 km SO_2 concentrations (both in ug/m^3) for 11 parks and park vulnerability ranks based on combined SO_2 sensitivities of lichens and SO_2 and O_3 sensitivities of vascular plants. Park codes are given in table 3. SO_2 symbols are the same as in figure 8.

Mountains, Sequoia-Kings Canyon, Acadia, Saguaro, and possibly Yosemite. All of these parks appeared in the high probability of injury quadrants of the risk analysis graphs. Craters of the Moon and Rocky Mountain have just been surveyed this year and no O_3 injury was found. SO_2 injury to vascular plants has not yet been reported from any of the Class I national parks but is being currently investigated. Anecdotal reports of lichen effects from SO_2 have been reported for Olympic, Acadia, Great Smoky Mountains and have been found in Shenandoah, all of which confirms the high risk portion of the analysis. No parks that occurred in the lower right quadrant of the plots, i.e. parks with low probabilities of current vegetation injury, have any current vegetation injury according to our surveys.

In several analyses it appears as if the majority of parks with possible injury occur in the western U.S. This may be due to the fact that 42 out of the 48 Class I national parks occur west of the Mississippi River, i.e. only six occur in the eastern U.S. Thus, any geographic patterns to the park vulnerabilities should not be given serious consideration.

The risk analysis is based on pollutant concentration data drawn from monitoring stations proximate to, but not actually in national parks units. The use of two cutoff distances for SO_2 stations allowed us to compare parks which may experience elevated SO_2 levels at differing points in time.

Parks that had high SO_2 data at 100 km stations compared to the 50 km stations may experience elevated SO_2 values farther in the future than parks with higher SO_2 concentrations at the 50 km stations. For example, Saguaro had a very high 100 km SO_2 value which was almost ten times higher than its 50 km value (probably due to more distant copper smelters), while Olympic's 50 km value was about 1.5 times higher than its 100 km value. Thus Olympic is more likely to experience elevated SO_2 than Saguaro in the near future. This type of discussion does not generally apply to O_3 because it is regarded as a regional pollutant.

The analysis described herein includes park vegetation sensitivities only to SO_2 and O_3. Other data are currently being assembled to factor in other pollutants, such as acid rain. If data were available on heavy metal levels in national parks this stress factor could also be incorporated. Adding more pollutants to the study would presumably add to its value for planning purposes, but would not improve the study's accuracy. At this point in time, however, the study has already been used in NPS planning. We hope to perform the analysis repeatedly as new sensitivity information becomes available.

ACKNOWLEDGMENTS

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