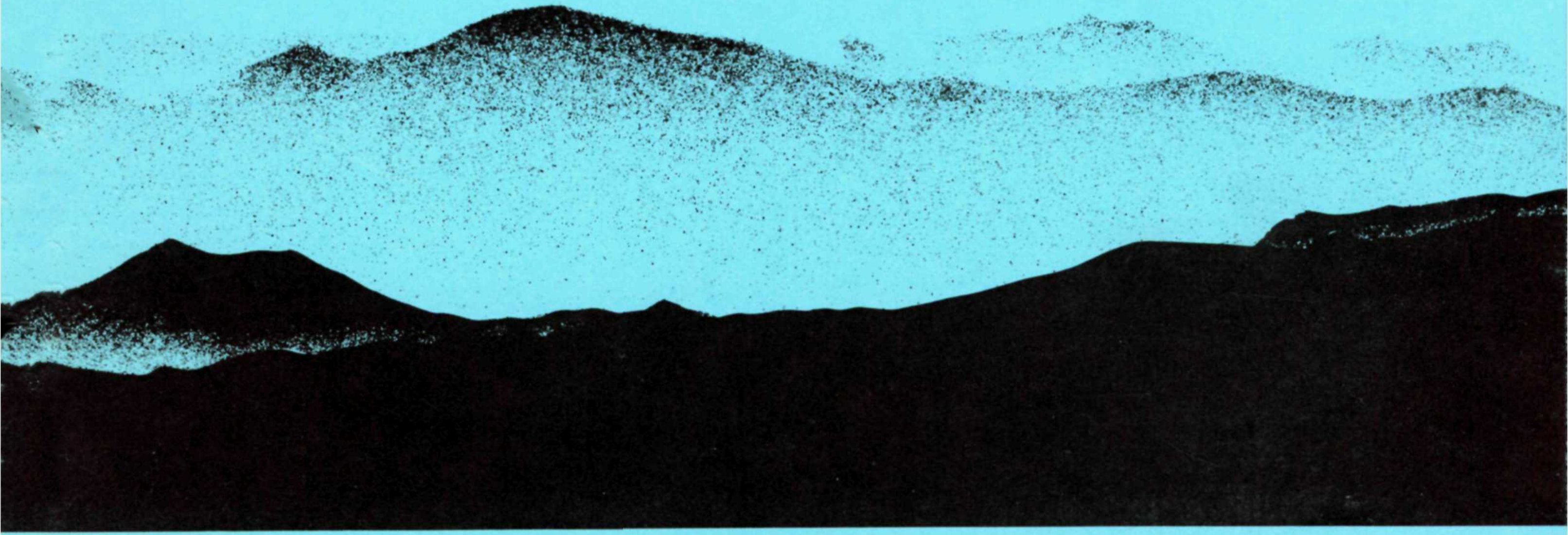
# Status of Air Quality and Related Values in Class I National Parks and Monuments of the Colorado Plateau

April 1997



NATIONAL
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The National Park Service, Air Resources Division, is responsible for preserving, protecting, and enhancing air quality and "air quality related values" in the National Park System by ensuring compliance with the requirements of the Clean Air Act and the National Park Service Organic Act. Air quality related values include visibility, flora, fauna, cultural and historical resources, soil, water quality, and virtually all resources that are dependent upon and affected by air quality. The Air Resources Division monitors air quality; reviews applications for proposed pollution sources, air quality legislative and regulatory proposals, and National Park Service and other federal or state air quality plans; develops data on sensitive park resources; and develops meteorology and atmospheric dispersion modeling.

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## Executive Summary

The National Parks and Monuments of the Colorado Plateau receive millions of visitors each year, attracted by outstanding scenic vistas and ecosystems that approach pristine conditions for the American West. Air quality is fundamentally important; imposing scenery needs to be visible to be appreciated. The potential impacts of changing air quality on ecosystems may be more subtle, including changes in the physiology of sensitive species which could lead to changes in community composition.

This project was initiated by the Air Resources Division of the National Park Service, with the objectives of summarizing:

1) Air quality and atmospheric deposition;
2) Sensitivity of terrestrial and aquatic ecosystems;
3) Current status of air quality related values (AQRVs);
4) Likely future status of AQRVs based on potential future air quality and ecosystem sensitivity;
5) Key areas requiring further research to clarify current impacts or likely future impacts.

The NPS has responsibility for 9 Class I areas in the Colorado Plateau: Arches National Park (ARCH), Black Canyon of the Gunnison National Monument (BLCA), Bryce Canyon National Park (BRCA), Canyonlands National Park (CANY), Capitol Reef National Park (CARE), Grand Canyon National Park (GRCA), Mesa Verde National Park (MEVE), Petrified Forest National Park (PEFO) and Zion National Park (ZION). This report also covers two nearby areas that are not generally considered as part of the Colorado Plateau: Bandelier National Monument (BAND) and Great Sand Dunes National Monument (GRSA).

The only documented impacts of air pollution on AQRVs in the Colorado Plateau involve visibility reductions. Air quality in this region is generally the best in the contiguous U.S., but visibility is moderately reduced for a substantial portion of the year for all Class I areas. Most of the atmospheric light extinction on the Colorado Plateau results from roughly equal contributions of sulfate, organics, and soot aerosols. Reductions in visibility from sulfate may be marginally alleviated in the future, depending on the degree to which emissions of $SO_2$ are reduced from existing sources or increased by additions of new point sources. Given that low-visibility days are due in large part to high concentrations of sulfate aerosols, any increase or decrease in S emissions should directly affect visibility.

No effects of ozone have been reported on the Colorado Plateau. Very little work has focused on the sensitivity of plants in this region to ozone. In general, the peak concentrations of ozone are low relative to the concentrations expected to produce visible injury to plants from other regions. Some recorded peaks have been high enough that some injury might be expected, but 1) no injury has been reported, and 2) high water stress may reduce plant exposure to ozone by reducing stomatal conductance. The levels of cumulative ozone exposure (calculated as the sum of the parts-per-billion in excess of 60 for 12 hr/day for 90 days) in some cases fall within the range where chronic effects (such as growth reductions) may be expected. However, no systematic surveys have examined the Class I areas of the Colorado Plateau for foliar injury or growth reductions. We expect that any current impact of ozone exposure on plants probably ranges from negligible to minor, but a systematic survey is recommended (see below). Ambient concentrations of $SO_2$ are far below thresholds for impacts on sensitive plants.

In general, surface waters and watersheds of the Colorado Plateau are resistant to chemical change due to low levels of acidic deposition and to the nature of the region's hydrogeology. Some of the park units discussed in this review have some portions that are characterized by bedrock resistant to weathering (e.g. Great Sand Dunes National Monument). Small pools, ponds, and streams found on more crystalline rock may be susceptible to change due to atmospheric inputs. A potentially important data gap is the potential for aquatic system change due to nitrogen inputs to both the aquatic and terrestrial ecosystems of the Colorado Plateau. Current rates of deposition probably exceed pre-industrial conditions, but no impacts on AQRVs are apparent. The NADP monitoring data show significant declines in S deposition at some sites on the Plateau, and no trends in N deposition.

## Recommendations

Our synthesis showed that visibility differs among the Parks and Monuments of the Plateau. Therefore, air quality at one location cannot in general be extrapolated simply from other sites because of differences in major sources of pollution, distances from sources, and weather patterns. Regional visibility conditions are currently assessed using the IMPROVE Protocol at several sites on the Colorado Plateau; other Class I areas of the Plateau have limited or no visibility monitoring. We recommend:

- Additional monitoring for specific units and resources for special studies, including more work to identify the contribution of specific point sources and of urban centers (particularly Las Vegas and urban centers in California) to visibility impairment.

No impacts on AQRVs have been reported for ozone; the lack of injury reports could indicate no effects have occurred, or a lack of a thorough reconnaissance by experts who can identify foliar injury. We recommend:

- A reconnaissance survey of all Class I NPS areas to determine if foliar injury from ozone is occurring. A single late-summer expedition would show the extent of any current problem and whether follow up surveys (in more depth) are warranted. This reconnaissance-level survey could be repeated after any summer with notably high ozone concentrations.

The monitoring of effects of deposition (both wet and dry) on surface waters needs to be continued or expanded. No estimates of rates of dry deposition are currently available for the Colorado Plateau. We recommend:

- An attempt be made to estimate dry deposition rates. This work would need to examine and improve the algorithms that are currently used to translate ambient concentrations of dry species to deposition loadings.

Too little is known about the biogeochemistry of small ponds and rock pools to know if increasing deposition of N (or S) could alter these unique ecosystems. We expect no major impacts at present, but we recommend:

- pH, ANC, sulfate-S, ammonium-N, and nitrate-N, and biological properties should be monitored for water bodies with ANC < 200 μeq/L and those on resistant bedrock (such as quartzite). Park staff review the surface water chemistry data with USGS researchers periodically to identify waters that might be sensitive to changes due to deposition.

The National Park Service has a policy and obligation to develop baseline inventories of the natural resources protected within the National Parks and Monuments. Most parks have incomplete species lists, only partial geographic information on location of species and communities, and few have any monitoring program that would identify moderate changes in ecosystem health. Substantial changes in vegetation are likely to develop in the coming decades, as a result of natural succession processes, fire regimes (including suppression, prescribed fire, and wildfire), responses to grazing (or cessation of grazing), visitor impacts, impacts of changing wildlife populations, and from driving forces such as pollution and climate change. The role of pollution in these changes can only be determined by adequate characterization of the nature and extent of changes, coupled with experimental information to determine the likely causes of the changes. We recommend:

- That broad-based resource monitoring in the Parks and Monuments be given a high priority.

Monitoring activities need to be supplemented by process-level experimentation to identify the likely AQRV impacts of air pollutants. We recommend:

- An experimental focus on the episodic change in chemistry of sensitive water during large events. Sensitive systems are most likely to show changes in chemistry and biota following large rain storms that flush accumulated dry deposition in small pools and streams. Where appropriate, rainfall events could be monitored, and short term responses in stream or pool chemistry could be studied (using automatic sampling devices). Before reaching conclusions about the effect of chemical changes on biota, controlled dose/response experiments would be needed (using native vertebrate and invertebrate species).
- A wide range of plant species needs to be screened in controlled fumigation experiments for sensitivity to ozone (in the range of 40 to 60 ppb average, with peak exposures of 100-120 ppb). These fumigations need to include manipulations of water supply (for at least a subset of the species) to examine the effects of moisture stress on reducing the ozone impacts on the plants. Another possible approach for examining potential impacts of current ozone levels would be testing plants on-site in charcoal-filtered air; open top chambers could be placed around established plants with and without filtered air treatments. Any increased growth in the filtered chambers would be consistent with an ozone-induced effect on growth.
- The pollutant of most concern relative to setting of critical loads is N because of the likely increase in the emissions of nitrogen oxides and ammonia due to human activities. Experimental additions of N (on the order of 10 to 20 kg N $ha^{-1}$ $yr^{-1}$) are needed to a

wide variety of ecosystems (from grasslands, shrublands and forests to potholes and streams) to provide a basis for insights about critical loads of N deposition in the Colorado Plateau.

We conclude that air quality in the Colorado Plateau is generally good; the major AQRV known to be impacted currently is visibility. No major or rapid changes are expected in the next decade or two; gradual changes in emissions may produce discernible changes in visibility. Research is needed to determine if AQRV of vegetation and surface waters are being affected at current levels of pollution.

## Acronyms, Abbreviations, and Units

| | |
|---|---|
| A.D. | *Anno Domini* |
| ADP | Adenosine Diphosphate |
| AIRS | Aerometric Information Retrieval System |
| ANC | Acid Neutralizing Capacity |
| AQRV | Air Quality Related Value |
| ARCH | Arches National Park |
| ARD | Air Resources Division (of the National Park Service) |
| ATP | Adenosine Triphosphate |
| $b_{ext}$ | Atmospheric Extinction Coefficient |
| BAND | Bandelier National Monument |
| BLCA | Black Canyon of the Gunnison National Monument |
| BLM | Bureau of Land Management |
| BRCA | Bryce Canyon National Park |
| CANY | Canyonlands National Park |
| CARE | Capitol Reef National Park |
| CO | Carbon Monoxide |
| $^{14}CO_2$ | Carbon Dioxide ($^{14}C$ isotope) |
| EPA | U.S. Environmental Protection Agency |
| GCVTC | Grand Canyon Visibility Transport Commission |
| GIS | Geographic Information System |
| GRCA | Grand Canyon National Park |
| GRSA | Great Sand Dunes National Monument |
| $H^+$ | Hydrogen Ion |
| $HNO_3$ | Nitric Acid |
| $H_2SO_4$ | Sulfuric acid |
| $HSO_3^-$ | Bisulfite |
| IMPROVE | Interagency Monitoring of Protected Visual Environments |

| | |
|---|---|
| IPCC | Intergovernmental Panel on Climate Change |
| MEVE | Mesa Verde National Park |
| MOHAVE | Project MOHAVE, EPA study of air flow and pollution transport |
| N | Nitrogen |
| NAAQS | National Ambient Air Quality Standards |
| NADP | National Atmospheric Deposition Program |
| NAPAP | National Acid Precipitation Assessment Program |
| NAWQA | National Ambient Water Quality Assessment |
| $N_2$ | Dinitrogen |
| $N_2O$ | Nitrous Oxide |
| $NH_3$ | Ammonia |
| $NH_4^+$ | Ammonium |
| NM | National Monument |
| $NO_2$ | Nitrogen Dioxide |
| $NO_2^-$ | Nitrite |
| NO | Nitric Oxide |
| $NO_x$ | Nitrogen Oxides |
| $NO_3^-$ | Nitrate |
| NP | National Park |
| NPS | National Park Service |
| O | Oxygen Atom |
| $O_2$ | Molecular Oxygen |
| $O_3$ | Ozone |
| OH- | Hydroxyl |
| PAN | Peroxylacyl Nitrate |
| PEFO | Petrified Forest National Park |
| PM | Particulate Matter |
| $PM_{10}$ | Particulate Matter (diameter less than 10 microns) |
| PSD | Prevention of Significant Deterioration |
| S | Sulfur |
| SCENES | EPA Study on Visibility |
| $SO_2$ | Sulfur Dioxide |
| $SO_3^{2-}$ | Sulphite |
| $SO_4^{2-}$ | Sulfate |
| $SO_x$ | Sulfur Oxides |
| SVR | Standard Visual Range |
| U.S. | United States |
| USDA | U.S. Department of Agriculture |
| USFS | U.S. Forest Service |
| USGS | U.S. Geological Survey |
| USFWS | U.S. Fish and Wildlife Service |

| | |
|---|---|
| VOC | Volatile Organic Compounds |
| WHITEX | Winter Haze Intensive Tracer Experiment |
| ZION | Zion National Park |

## Units

| | |
|---|---|
| $^{o}$C | degrees Celsius |
| cm | centimeter |
| dv | deciviews |
| g | gram |
| ha | hectare |
| hr | hour |
| kg | kilogram |
| km | kilometer |
| L | liter |
| m | meter |
| mg | milligram |
| mm | millimeters |
| Mm | megameters |
| MW | megawatt |
| μeq | microequivalent |
| μg | microgram |
| μm | micrometers |
| μS | microsiemens |
| ppb | parts per billion |
| yr | year |

# Chapter 1. Introduction: Policy, Monitoring, and Synopsis of Air Quality on the Colorado Plateau

The National Parks (NP) and National Monuments (NM) of the Colorado Plateau receive millions of visitors each year, attracted by outstanding scenic vistas and ecosystems that approach pristine conditions for the American West. Air quality is fundamentally important; imposing scenery needs to be visible to be appreciated. The potential impacts of changing air quality on ecosystems may be more subtle, including changes in the physiology of sensitive species which could lead to changes in community composition.

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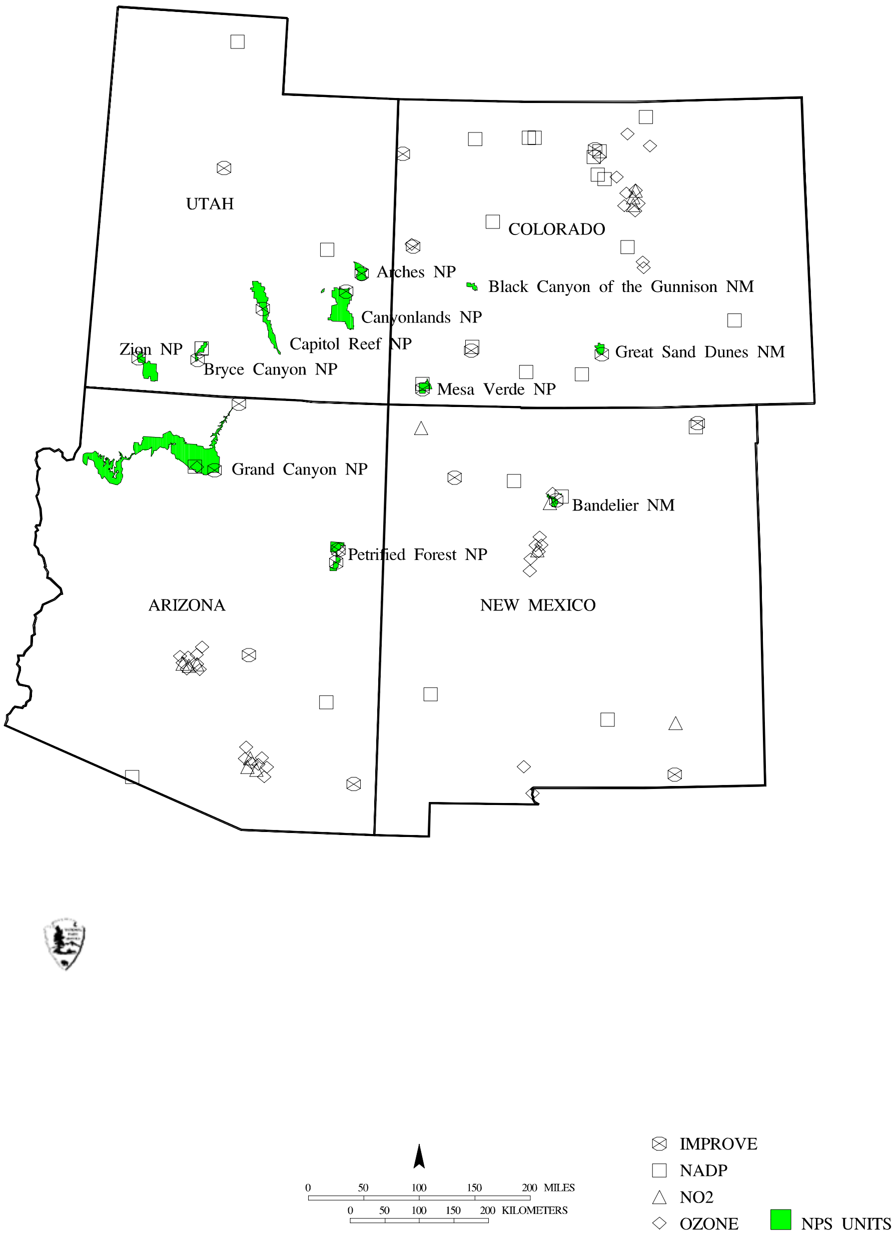
The NPS has responsibility for 9 Class I areas in the Colorado Plateau (Figure 1-1): Arches National Park (ARCH), Black Canyon of the Gunnison National Monument (BLCA), Bryce Canyon National Park (BRCA), Canyonlands National Park (CANY), Capitol Reef National Park (CARE), Grand Canyon National Park (GRCA), Mesa Verde National Park (MEVE), Petrified Forest National Park (PEFO) and Zion National Park (ZION). This report also covers two nearby areas that are not generally considered as part of the Colorado Plateau: Bandelier National Monument (BAND) and Great Sand Dunes National Monument (GRSA).

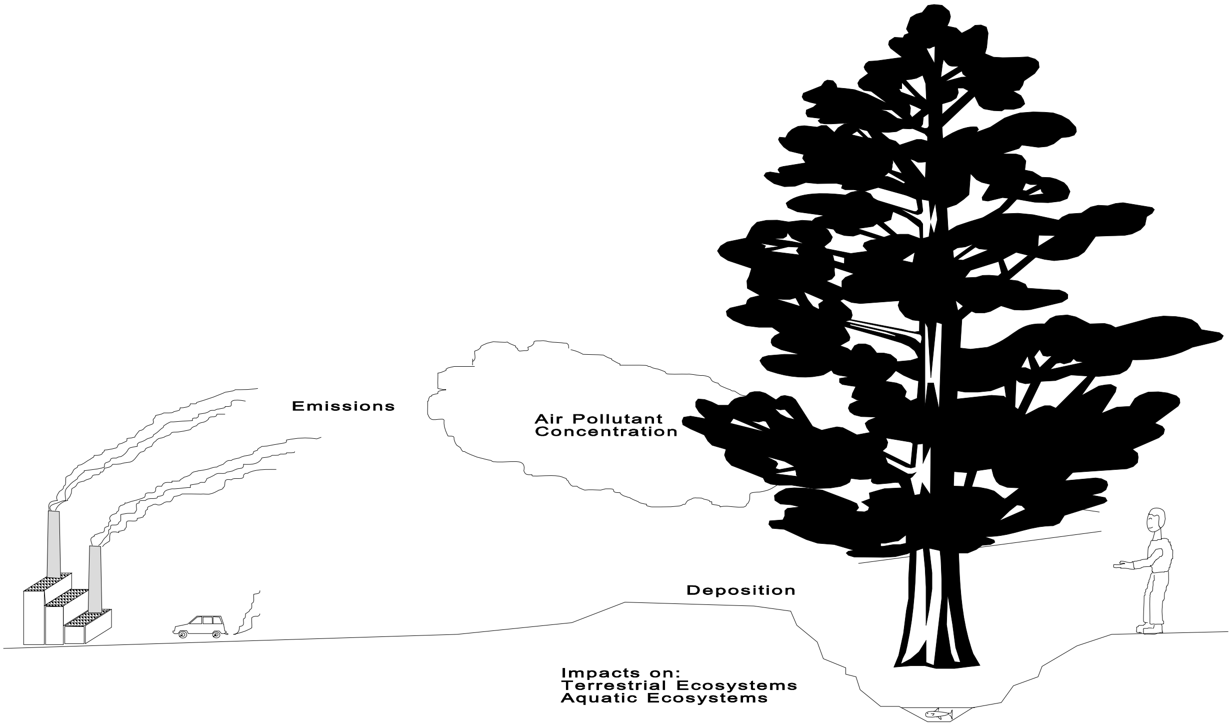
This assessment begins with an overview of the key features of air quality in the Colorado Plateau and the potential sensitivity of air quality related values. Individual chapters focus on each Class I area by following the flow of pollutants from emissions, to air concentrations (and effects on visibility), to deposition and effects on terrestrial and aquatic ecosystems (Figure 1-2). A final chapter synthesizes the overall picture for Class I areas of the Colorado Plateau (and nearby areas) administered by the NPS, and makes recommendations for future research.

Figure 1-1. Class I National Parks and Monuments of the Colorado Plateau.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS



This introductory chapter summarizes major features of air quality policy for Class I areas, and then provides a synoptic view of major features of air quality around the Colorado Plateau, with some comparisons with the nation as a whole. The presence of pollutants in the atmosphere directly influences visibility values of landscapes, and we describe the key aspects of visibility and how they have been monitored on the Colorado Plateau. Other pollutants, like ozone, directly damage vegetation; we describe the monitoring programs in the area and the regional scale information on concentrations of gaseous pollutants. The introductory chapter concludes by describing the monitoring efforts that gauge rates of deposition of pollutants from the atmosphere to ecosystems, and how they might affect terrestrial and aquatic ecosystems.

## Air Quality Policy in National Parks and Monuments

One of the purposes of the 1977 Clean Air Act Amendments is to “preserve, protect, and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historic value” (Section 160). The Act provides for greatest protection in “Class I" areas, defined as national parks over 2,430 ha and national wilderness areas over 2,020 ha that were in existence before August of 1977. According to the Clean Air Act and its amendments, federal land managers have "...an affirmative responsibility to protect the air quality related values (AQRVs)...within class I areas" (Clean Air Act section 165(d)(2)(B); Eilers et al. 1994).

Human activities produce a wide variety of air pollutants, with various potential effects on humans and ecosystems. The U.S. Environmental Protection Agency (EPA) established National Ambient Air Quality Standards (NAAQS) to protect human health (primary) and public welfare (secondary). Some of these pollutants, such as carbon monoxide and lead, may have greater effects on human health than on wildland ecosystems. Other pollutants, such as ozone, may have substantial effects on ecosystems at thresholds below the human-health standards (see Chapter 2).

Table 1-1. National Ambient Air Quality Standards (NAAQS) in $\mu g/m^3$ (40 C.F.R. part 50), increments allowed above baseline in Class I areas, that may prevent significant deterioration (PSD), and proposed (July 23, 1996) significant levels that represent increments which would trigger a cumulative increment analysis.

| Pollutant | Averaging time | Primary | Secondary | Increments | Significant levels |
|---|---|---|---|---|---|
| Sulfur dioxide | Annual arith. | 80 | none | 2 | 0.1 |
| | 24-hour[1] | 365 | none | 5 | 0.2 |
| | 3-hour[1] | none | 1300 | 25 | 1.0 |
| $PM_{10}$[2] | Annual arith. | 50 | same | 4 | 0.2 |
| | 24-hour | 150 | same | 8 | 0.3 |
| Carbon monoxide | 8 hour[1] | 10000 | same | none | none |
| | 1-hour[1] | 40000 | same | none | none |
| Ozone | 1-hour[3] | 235 | same | none | none |
| Nitrogen dioxide | Annual arith. | 100 | same | 2.5 | 0.1 |
| Lead | Calendar quarter | 1.5 | same | none | none |

[1] Maximum concentration not to be exceeded more than once per year.

[2] $PM_{10}$ = particulate matter with diameter < 10 μm.

[3] This standard is attained when the number of days per calendar year with the maximum hourly average concentrations above the standard is equal to or less than one.

Some revision of these primary standards are being considered. The EPA issued an announcement on November 27, 1996 of proposed revisions, including:

- a $PM_{2.5}$ (particulate matter < 2.5 μm) of 50 $\mu g/m^3$ for 24 hr average (annual mean of 15 $\mu g/m^3$);
- a primary ozone standard of 80 ppm for 8 hr average; and
- a secondary ozone standard of a seasonal SUM60 (sum of hourly ozone concentrations in excess of 60 ppb for 12 hr/day for 3 months) for protection of plants.

In addition to these “criteria” pollutants that may affect human health and welfare, ecosystems may be sensitive to deposition of acidity, sulfur (S) and nitrogen (N) compounds, and heavy metals, and visibility may be impaired by a variety of particulates. Areas that meet the standards may still experience substantial impacts from poor air quality. Therefore, air quality in Class I areas involves provisions of the Clean Air Act that aim to “prevent significant deterioration”. The permitting process for new point sources of pollution, and major modification of existing point sources, requires that the new source will not violate state or national ambient air quality standards, will use the best available control technology to limit emissions, and will not harm AQRVs in any Class I area (Peterson et al. 1992, Bunyak 1993, Eilers et al. 1994).

Air quality related values include: visibility, plants, animals, soils, surface waters, historic and geologic resources, and virtually any other resource affected by air quality. The information base is strong for some AQRVs for Class I areas of the Colorado Plateau, but very weak in others. This assessment does not consider the effects of air quality on cultural values.

### Air Quality Monitoring in Class I National Parks and Monuments of the Colorado Plateau

Across the United States (U.S.), many parameters of air quality have improved over the past two decades (EPA 1995). In the past 10 years, average national concentrations of lead declined by 86%, carbon monoxide (CO) by 28%, sulfur dioxide ($SO_2$) by 25%, and ozone ($O_3$) by 12%. The Colorado Plateau has typically experienced the best air quality in the continental United States. A wide range of monitoring, research, and case studies have measured levels of various pollutants across the Colorado Plateau for varying lengths of time (Figure 1-3). The length of record is variable for these programs, but most of the active sites have records spanning from 5 to 8 years. The NPS monitors visibility conditions and supports studies to determine the causes of visibility impairment (haze and plumes) at many parks and wilderness areas nationwide. The purpose of this monitoring is to establish the spectrum of current visibility conditions, identify the specific chemical species and the emission sources that contribute to visibility impairment, and to document long-term trends to assess the effects of changes in emissions. The NPS cooperates and shares resources with other federal land managing agencies, states, and the EPA in the Interagency Monitoring of Protected Visual Environments (IMPROVE) program (Sisler et al. 1993). On the Plateau, IMPROVE monitoring is conducted at Arches NP, Bandelier NM, Bryce Canyon NP, Canyonlands NP, Grand Canyon NP, Great Sand Dunes NM, Mesa Verde NP, and Petrified Forest NP. The NPS also participates in the National Atmospheric Deposition Program (NADP) which monitors the chemistry and quantity of precipitation across the U.S., including 10 stations in the Colorado Plateau area. The NPS conducts routine monitoring of ozone in selected national parks and monuments, with data available from the Aerometric Information Retrieval System (AIRS), administered by the EPA.

Table 1-2. Air quality monitoring in Class I National Parks and Monuments of the Colorado Plateau.

| National Park or Monument | Ozone | NADP (deposition) | $SO_2$ concentration | Visibility |
|---|---|---|---|---|
| Arches | 88-92 | Nearby (Green River, 1985-present) | 1988-1992 | Camera 1986-1991<br>IMPROVE sampler 1988-1992 |
| Bandelier | 90-94 | 1982-present[1] | 1988-1992 | Transmissometer 1988-present; Camera 1978-1995; IMPROVE sampler 1988-present |
| Black Canyon of the Gunnison | 95-96 (passive) | No | No | Camera 1985-1993 |
| Bryce Canyon | 95-96 (passive) | 1985-present | 1988-1989, 1991-1992 | Camera 1979-present<br>IMPROVE sampler 1988-present |
| Canyonlands | 92-present | Nearby (Green River, 1985-present) | 1988-1989, 1991-present | Transmissometer 1987-present; Camera 1982-1995; IMPROVE sampler 1988-present |

| | | | | |
|---|---|---|---|---|
| Capitol Reef | 95-96 (passive) | Nearby (Green River, 1985-present) | No | Camera 1985-1991 |
| Grand Canyon | 83, 89-present | 1981-present | 1988-1989; 1991-present | Transmissometer 1986-present; camera 1979-present; IMPROVE sampler 1988-present |
| Great Sand Dunes | 88-91 | Nearby (Alamosa, 1980-present) | 1988-1992 | Camera 1987-1995; IMPROVE sampler 1988-present |
| Mesa Verde | 93-present | 1981-present | 1991-1992 | Transmissometer 1988-1993; camera 1979-1995 IMPROVE sampler 1988-present |
| Petrified Forest | 87-91 | No | 1988 | Transmissometer 1987-present; camera 1986-1995; IMPROVE sampler 1988-present |
| Zion | 95-96 (passive) | No | No | Camera 1985-1991 |

[1] Present = 1996

## *IMPROVE Station Description and Rationale*

Visibility impairment results from both absorption and scattering of light by particles suspended in the air. "Fine" particles < 2.5 μm and gases with molecular diameters on the order of 0.0001 μm are especially efficient at scattering light. Scattering of light by fine particles and gases accounts for the majority of visibility impairment in the Colorado Plateau. Scattering by "air" molecules (Rayleigh scattering) causes the sky to appear blue, and sets the limit on the best possible visibility for a specific geographic location.

A fully complemented IMPROVE station includes monitoring of fine and coarse particle concentrations (particles with diameters < 10 μm, these particles do not scatter light well and therefore do not contribute much to visibility impairment) optical conditions, and view monitoring with photography. Water vapor in the air can affect visibility, so most stations also record temperature and relative humidity. Particle monitoring provides concentration measurements of specific chemicals that contribute to visibility impairment and involves sets of four samplers that automatically collect two 24-hr samples each week (Wednesday and Saturday from midnight to midnight) by drawing air through filters. The filters capture suspended particles that are then sent for laboratory analyses to determine the mass and chemical composition of the particles. One sampler collects coarse particles and the other three collect fine particles with diameters <2.5 μm. The three fine particle samples are analyzed for elemental composition and mass, mass of sulfate and nitrate, and mass of carbon species. These masses and air flow information are used to determine concentrations and are reported quarterly.

Optical monitoring provides a quantitative measure of light extinction (light attenuation per unit distance) to represent visibility conditions. Optical monitoring uses long-path transmissometers and nephelometers. Transmissometers measure the amount of light transmitted through the atmosphere over a known distance (between 0.5 and 10 km) between a light source of known intensity (transmitter) and a light measurement device (receiver). The transmissometer measurements are electronically converted to hourly averaged light extinction (scattering plus absorption). Nephelometers draw air into a chamber and measure the scattering component of light extinction.

View monitoring provides a photographic record of visibility conditions. View monitoring is accomplished with automated 35-mm camera systems. These cameras take three shots a day at fixed times of selected scenes. The resulting slides are used to facilitate data interpretation, display anticipated changes in visibility, and form a photographic record of characteristic visibility conditions.

A more detailed description of the visibility and particle monitoring network may be found in Sisler et al. (1993).

### *Visibility Characterization*

Visibility is usually characterized by visual range (the greatest distance that a large black object can be seen against the horizon sky background) or extinction (the attenuation of light per unit distance). These two characterizations are inversely related; a great visual distance relates to a very low light extinction. Visual range is useful for safety reasons such as to direct aircraft traffic near airports, but it is not particularly useful for assessing the quality of scenic vistas that include color, texture, and other details. Nonetheless, visual range remains a useful measure for describing overall visibility, especially for communication with visitors to parks and monuments.

Extinction (expressed as inverse megameters ($Mm^{-1}$)) is a better characterization of visibility impairment and is more directly related to scenic quality. Extinction can be directly measured or derived from measured particle concentrations ("reconstructed extinction"). Also, "extinction budgets" can be prepared which show the relative contribution of each atmospheric constituent (particles and/or gases) to extinction. With these extinction budgets, one can display the relative importance of each constituent to impairment and estimate changes in visibility conditions due to changes in the concentrations of the constituents which may be caused by emission increases or decreases

A drawback to both of these extinction characterizations is that the effect of a specific change (such as 2 $Mm^{-1}$) may be small or large, depending on background conditions.

Another visibility characterization, the deciview, has been derived to index a constant fractional change in extinction or visual range (Pitchford and Malm 1994). The advantage of this characterization is that equal changes in deciview are equally perceptible across different baseline conditions.

### *Overview of Conditions Across the Colorado Plateau*

The IMPROVE monitoring network currently has 55 sites, with 6 sites on the Colorado Plateau. Figure 1-3 shows isopleths of the total reconstructed light extinction (including Rayleigh, which is about 10 $Mm^{-1}$) for each of the reported sites in the IMPROVE network for the period March 1988 through February 1994. The highest reconstructed light extinction (>100 $Mm^{-1}$) occurs in the southeastern U.S. while the Colorado Plateau and the Great Basin have the lowest extinctions. Regionally averaged visual ranges are presented in Figure 1-4, and again the Colorado Plateau (along with the Great Basin and central Rockies) has the best visibility conditions in the continental U.S.

Figure 1-4. Transmissometer visibility monitoring sites for geographic regions.

**Visibility Metric:**

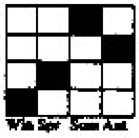
| | |
|---|---|
| **Average conditions...** | **Arithmetic mean of all visibility data for all regions**<br>**(Visual Range = 78 km, $b_{ext}$ = 50 $Mm^{-1}$)** |
| **Best conditions...** | **Arithmetic mean of the 20% least impaired visibility data for all regions.**<br>**(Visual Range = 145 km, $b_{ext}$ = 27 $Mm^{-1}$)** |
| **Worst conditions...** | **Arithmetic mean of the 20% most impaired visibility data for all regions.**<br>**(Visual Range = 45 km, $b_{ext}$ = 95 $Mm^{-1}$)** |

**Box Plot Key:**

**Columns - Represent Meteorological Seasons**
- **Column 1 - Winter (December, January, and February)**
- **Column 2 - Spring (March, April, and May)**
- **Column 3 - Summer (June, July, and August)**
- **Column 4 - Autumn (September, October, and November)**

**Rows - Represent Defined Visibility Ranges**
- **Row 1 - Average seasonal visibility is in the "Worst" visibility metric category.**
- **Row 2 - Average seasonal visibility is in the "Below Average" visibility metric category.**
- **Row 3 - Average seasonal visibility is in the "Above Average" visibility metric category.**
- **Row 4 - Average seasonal visibility is in the "Best" visibility metric category.**

**Example Box Plot:**



| | |
|---|---|
| **"Worst"** | **Visual Range less than 41 km ($b_{ext} \geq 95$ $Mm^{-1}$)** |
| **"Below Average"** | **Visual Range from 41 km to 78 km ($b_{ext}$ from 95 $Mm^{-1}$ to 50 $Mm^{-1}$)** |
| **"Above Average"** | **Visual Range from 78 km to 145 km ($b_{ext}$ from 50 $Mm^{-1}$ to 27 $Mm^{-1}$)** |
| **"Best"** | **Visual Range greater than 145 km ($b_{ext} < 27$ $Mm^{-1}$)** |

Table 1-3. Transmissometer visibility monitoring sites for geographic regions in Figure 1-4.

| Region | Transmissometer Monitoring Sites |
|---|---|
| Appalachian Mountains | Shenandoah National Park - Virginia |
| Central Rocky Mountains | Bridger Wilderness - Wyoming<br>Rocky Mountain National Park - Colorado<br>Yellowstone National Park - Wyoming |
| Coastal Mountains | Pinnacles National Monument - California |
| Colorado Plateau | Bandelier National Monument - New Mexico<br>Canyonlands National Park - Utah<br>Grand Canyon National Park - Arizona<br>Mesa Verde National Park - Colorado<br>Petrified Forest National Park - Arizona |
| Great Basin | Great Basin National Park - Nevada |
| Northeast | Acadia National Park - Maine |
| Northern Great Plains | Badlands National Park - South Dakota |
| Northern Rocky Mountains | Glacier National Park - Montana |
| Sierra Nevada | Yosemite National Park - California |
| Sonoran Desert | Chiricahua National Monument - Arizona |
| Southern California | San Gorgonio Wilderness - California |
| West Texas | Big Bend National Park - Texas<br>Guadalupe Mountains National Park - New Mexico |

Light extinction on the Colorado Plateau derives primarily from scattering by fine particles (about 40% of total annual extinction, Table 1-4), and by natural Rayleigh scattering by atmospheric gases (32%). The remaining extinction results from scattering by coarse particles, and by absorption by particles and gases. The differences among seasons are small, with total extinction ranging from 29 $Mm^{-1}$ in the spring to 33 and 34 $Mm^{-1}$ during the summer and winter, respectively. As shown in Table 1-5, ammonium sulfate on the average, consistently accounts for about 30% of the particle extinction. Ammonium nitrate exhibits the strongest seasonal variation with its highest contribution being in the winter.

Table 1-4. Colorado Plateau extinction apportioned by general category ($Mm^{-1}$)

| Season | Total Extinction | Non-Rayleigh Extinction | Fine Scattering | Coarse Scattering | Absorption |
|---|---|---|---|---|---|
| Spring | 29.3 | 19.3 | 10.3 | 4.1 | 4.9 |
| Summer | 33.0 | 23.0 | 12.4 | 4.3 | 6.3 |
| Autumn | 30.7 | 20.7 | 12.1 | 2.9 | 5.6 |
| Winter | 33.8 | 23.8 | 16.5 | 2.1 | 5.2 |
| Annual | 31.5 | 21.5 | 12.7 | 3.4 | 5.5 |

Table 1-5. Contributions of various types of fine particles to the total non-Rayleigh light extinction for the Colorado Plateau ($Mm^{-1}$)

| Season | Particle Extinction | Ammonium Sulfate | Ammonium Nitrate | Organics | Carbon (soot) | Soil & Coarse Material |
|---|---|---|---|---|---|---|
| Spring | 19.3 | 5.1 | 1.2 | 3.9 | 4.9 | 4.1 |
| Summer | 23.0 | 6.0 | 0.8 | 5.6 | 6.3 | 4.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Autumn | 20.7 | 6.3 | 0.9 | 4.9 | 5.6 | 2.9 |
| Winter | 23.8 | 8.2 | 3.9 | 4.4 | 5.2 | 2.1 |
| Annual | 21.5 | 6.5 | 1.5 | 4.7 | 5.5 | 3.4 |

## Sources

In the Colorado Plateau, the major sources of sulfate ($SO_4^{2-}$, a secondary pollutant formed in the atmosphere from sulfur oxides, $SO_x$) are coal and oil-fired power plants, and refining and smelting activities. The primary sources of nitrate ($NO_3$, also a secondary pollutant formed from nitrogen oxides, $NO_x$) are automobiles and all other combustion sources. Organic pollutants can substantially affect visibility, and they derive from both natural sources (bioemissions), and from smoke and industrial solvents. Soot particles come from diesel exhaust and smoke, and coarse particles come from wind-blown dust, smoke, and pollen.

### *Case Studies of Visibility on the Colorado Plateau*

In addition to the IMPROVE network, the Colorado Plateau has been the focus of a variety of studies that examined visibility, haze, and the sources of pollutants responsible for visibility impairment. These studies have included:

- basic principal component/back-trajectory analyses (Malm 1989) which have identified southern California and southeastern Arizona as major contributors to haze at the Grand Canyon and regions to the northwest of the park as sources of clear air.
- the SCENES visibility monitoring (Mueller et al. 1986) for the Colorado Plateau. This was a cooperative study to identify visibility conditions on the Colorado Plateau.
- the 1987 Winter Haze Intensive Tracer Experiment (WHITEX) (Malm et al. 1989) which characterized the effect of the Navajo Generating Station on visibility in the Grand Canyon and resulted in sulfur dioxide emissions at that facility being reduced by 90%.
- the National Academy of Sciences evaluation of WHITEX (National Research Council 1990).
- Project MOHAVE, an EPA-sponsored tracer study to quantify the contribution of the Mohave power plant and western urban sources to haze at the Grand Canyon. The field study was

completed in 1992, but study results are not available as of June 1997.

- Grand Canyon Visibility Transport Commission (GCVTC), formed as a result of the Clean Air Act of 1990, to recommend methods of improving visibility throughout the Colorado Plateau by considering all sources of emissions in the western States that may impact the Plateau region.

*Visibility Projections*

The 1990 Clean Air Act mandated the establishment of the GCVTC to advise the EPA on strategies for protecting visual air quality in national parks and wilderness areas on the Colorado Plateau. The Commission was composed of the governors of eight western states (Arizona, California, Colorado, New Mexico, Nevada, Oregon, Utah and Wyoming), leaders of four tribes (Acoma, Hopi, Hualapai, Navajo), representatives of four federal land management agencies [U.S. Bureau of Land Management (BLM), U.S. Fish and Wildlife Service (USFWS), U.S. Forest Service (USFS), and NPS], representatives of the Columbia River Inter-Tribal Fish Commission, and the EPA. The Commission issued its final report in June of 1996 (GCVTC 1996). The Commission reviewed available information, developed data bases, and simulated various features of air quality.

Recommendations of the Commission include:

- Setting regional targets in 2000 for $SO_2$ emissions from stationary sources; exceedances would invoke a yet-to-be developed regulatory program which might include a market trading program for emissions.
- The Commission's research and modeling showed a wide range of sources of air pollution reaching Class I areas of the Colorado Plateau, including emissions from urban areas.
- The Commission concluded that both prescribed fires and wildfires are likely to increase in the coming decades as a result of previous efforts at fire suppression.
- The Commission recommended establishment of an on-going body similar to itself for addressing the continuing issues of air quality on the Colorado Plateau.

The GCVTC (1996) performed extensive computer modeling to examine contributions of regional and local pollutants to visibility impairment. Results suggest that long-range transport (>160 km) substantially contributed to haze in Class I areas of the Colorado Plateau; Grand Canyon visibility was affected by pollution from Los Angeles, and visibility at Canyonlands NP was affected by pollution from Salt Lake City. The Commission also concluded that local sources may be more important to production of haze than previously thought, particularly in windless periods. However, the report cautioned that years of technical work may be necessary before the relative visibility impacts of regional and local sources can be confirmed.

The Grand Canyon Visibility Transport Commission projected likely visibility for the Grand Canyon NP, Bryce Canyon NP, Canyonlands NP, and Mesa Verde NP through 2040, and the major species responsible for visibility impairment. Reduced emissions from utilities were projected to reduce light extinction by about approximately 1 $Mm^{-1}$. Light extinction caused by vehicle emissions was projected to decline until approximately 2005, and then increase through 2040. The dirtiest days have more than twice the visibility impairment of clean days with the bulk of the impairment resulting from human- related sources. Emissions from Mexico are increasing, contributing high quantities of sulfates to the air that reaches the Colorado Plateau.

The incidence of prescribed fires and wildfires is likely to increase in the coming decades as a result of past fire suppression, and fire-generated soot may substantially impair visibility. Historically, about 14 million ha of land burned annually across the region contributes to reduced visibility on the Colorado Plateau, with large variation among years. Current prescribed fire programs ignite only 0.5 million ha of land. Fire suppression for the past 80 years has resulted in large fuel accumulations, and millions of hectares of forests, shrublands and grasslands across the Colorado Plateau are at risk from catastrophic wildfire (GCVTC 1996). The Commission concluded that emissions from fire may represent the single most important change in air quality on the Colorado Plateau in the next 50 years.

The effects of fire on visibility are highly seasonal, with far greater effects for periods of days to weeks than on an annual average basis. Some of the best visibility occurs in winter on the Colorado Plateau, whereas fires occur in spring, summer and autumn. Therefore, increased fires would have little effect on the cleanest days, but would exacerbate visibility impairment on days that are already lower in visibility.

The Commission also evaluated the contributions of 95 source areas to visibility reduction at the Grand Canyon. They concluded that the greatest gains in visibility would come from reducing the tons of emissions from sources with large “transfer coefficients” (a relationship between the visibility impairment at a site and the magnitude of emission at the source).

## Ozone

Ozone concentrations on the Colorado Plateau have been monitored at several National Parks and Monuments using continuous monitors by ultraviolet photometric methods. Some sites were monitored in 1995 and 1996 by a passive ozone sampling system (see below).

The mean daily ozone concentrations for the growing season (May through September) are low across the Colorado Plateau (Table 1-6), typically falling between 40 and 50 ppb (24 hr mean). The “natural” concentration of ozone in the absence of pollution may have been between 30 and 50 ppb (Lefohn et al. 1990, EPA 1996), indicating modest increases over pre-industrial levels. No observations have exceeded the primary standard of 120 ppb, except for one occasion in 1991 in Petrified Forest, which recorded a value of 134 ppb. Across the Colorado Plateau, the cumulative exposures to ozone are relatively low. D. Joseph (NPS-ARD) calculated the “sum60" cumulative exposures for 3 month summer periods for 12 hr/day (Table 1-6). The cumulative exposures are commonly about 10000 ppb-hr or less, with notably higher concentrations for some years at Bandelier and Grand Canyon. The highest observed values came in 1991, reaching 28000 ppb-hr for Bandelier and 22000 ppb-hr for the Grand Canyon. These data indicate that peak concentrations of ozone are not likely to cause problems for plants, but that the possibility of damage from chronic exposure to moderate concentrations of ozone warrants examination (see Chapter 2).

Table 1-6. Ozone concentrations and exposures between May and September. Upper value is mean daily ozone concentration (ppb); middle number is the maximum 3-month “Sum60" exposure value (ppb in excess of 60, for 12 hr/day (ppb-hr)/yr; data provided by D. Joseph, ARD); and bottom number is the maximum 1-hr concentration observed each year (ppb). Percent of data capture varied among sites and years. Data from the NPS Air Resources Division’s Quick Look Annual Summary Statistics Reports.

| Year | Arches | Bandelier | Canyonlands | Grand Canyon | Great Sand Dunes | Mesa Verde | Petrified Forest |
|---|---|---|---|---|---|---|---|
| 1983<br>Mean<br>Sum60<br>Max | -- | -- | -- | 26<br>--<br>66 | -- | -- | -- |
| 1987<br>Mean<br>Sum60<br>Max | -- | -- | -- | -- | -- | -- | 42<br>18207<br>116 |
| 1988<br>Mean<br>Sum60<br>Max | 44<br>7597<br>70 | -- | -- | -- | 40<br>1863<br>76 | -- | 39<br>7611<br>101 |
| 1989<br>Mean<br>Sum60<br>Max | 45<br>6117<br>87 | -- | -- | 43<br>--<br>68 | 41<br>728<br>63 | -- | 43<br>20902<br>104 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1990 | | | -- | | | -- | |
| Mean | 28 | 48 | | 43 | 42 | | 40 |
| Sum60 | -- | 15200 | | -- | 4975 | | 13427 |
| Max | 56 | 81 | | 74 | 70 | | 97 |
| 1991 | | | -- | | | -- | |
| Mean | 36 | 48 | | 46 | 41 | | 41 |
| Sum60 | -- | 28265 | | 21923 | 6598 | | 14802 |
| Max | 74 | 87 | | 79 | 77 | | 134 |
| 1992 | | | | | -- | -- | -- |
| Mean | 46 | 46 | 47 | 44 | | | |
| Sum60 | -- | 13070 | -- | 10416 | | | |
| Max | 76 | 78 | 65 | 78 | | | |
| 1993 | -- | | | | -- | | -- |
| Mean | | 44 | 47 | 46 | | 41 | |
| Sum60 | | 8490 | 4156 | 7228 | | 3280 | |
| Max | | 77 | 75 | 73 | | 67 | |
| 1994 | -- | | | | -- | | -- |
| Mean | | 46 | 51 | 49 | | 45 | |
| Sum60 | | 19160 | 16023 | 12542 | | 7985 | |
| Max | | 90 | 73 | 79 | | 72 | |

### *Ozone Sampling with Passive Samplers (1995 and 1996)*

Given the low number (and high expense) of continuous ozone monitoring on the Colorado Plateau, several parks used Ogawa passive samplers in 1995 and 1996 (provided by J. D. Ray, ARD, Table 1-7). The passive samplers use nitrite-coated filter pads to collect ozone by diffusion to form nitrate. Exposed filters were returned to a commercial lab, and nitrate was determined by ion chromatography. These devices have an accuracy of about ±10% and a precision of better than 3% based on duplicate samples. Weekly values from the passive samplers in 1995 were divided by the number of hours of data collected to provide 1-hr average concentrations (Table 1-7). Comparable values were calculated for continuous ozone monitors at Mesa Verde and Grand Canyon. The average hourly ozone concentrations followed the weekly changes in regional weather. The parks where ozone was measured with the passive samplers were generally found to be slightly cleaner (41 to 46 ppb ozone) compared to the parks with continuous ozone monitors (49 to 54 ppb average). The ozone concentrations were strongly correlated among Capitol Reef, Black Canyon of the Gunnison, Grand Canyon, and Mesa Verde. Zion and Bryce Canyon correlated with each other, but not with the other parks.

Table 1-7. Average hourly ozone for weekly samples (ppb) based on weekly sample periods for 1995 (data from J. Ray, NPS-ARD).

| Month | Week | Black Canyon | Bryce Canyon | Capitol Reef | Zion | Mesa Verde |  | Grand Canyon |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | mean[1] | maximum[2] | mean[1] | maximum[2] |
|  |  | Passive monitoring |  |  |  | Continuous monitoring |  |  |  |
| May | 1 | 45.7 | 39.8 | 42.3 | 42.5 | 49.7 | 58 | 53.1 | 74 |
|  | 2 | 46.0 | 42.4 | 41.7 | 44.8 | 49.6 | 61 | 53.1 | 75 |
|  | 3 | 47.9 | 46.3 | 46.1 | 54.6 | 54.1 | 66 | 58.5 | 73 |
|  | 4 | 44.4 | 36.5 | 42.3 | 35.3 | 50.3 | 67 | 53.3 | 68 |
|  | 5 | 41.0 | 37.1 | 41.3 | 44.9 | 48.0 | 67 | 53.4 | 69 |
| June | 1 | 45.5 | 48.2 | 46.2 | 46.0 | 51.1 | 71 | 56.2 | 68 |
|  | 2 | 46.3 | 49.9 | 39.7 | 43.4 | 51.0 | 67 | 51.6 | 75 |
|  | 3 | 48.5 | 49.9 | 43.9 | 48.5 | 51.3 | 61 | 54.2 | 69 |
|  | 4 | 37.8 | 43.9 | - - | 41.3 | 43.9 | 57 | 53.8 | 72 |
| July | 1 | 47.1 | 49.9 | 43.5 | 45.5 | 50.8 | 67 | 55.7 | 69 |
|  | 2 | 36.6 | 43.4 | 37.5 | 44.0 | 41.9 | 56 | 47.5 | 65 |
|  | 3 | 40.3 | 49.3 | 41.3 | 51.6 | 46.1 | 56 | 54.3 | 73 |
|  | 4 | 47.7 | 50.6 | 46.1 | 52.4 | 50.4 | 63 | 56.4 | 67 |
| Aug | 1 | 53.0 | 55.2 | - - | 46.8 | - - | - - | - - | - - |
|  | 2 | 45.5 | 47.8 | - - | 39.5 | - - | - - | - - | - - |
|  | 3 | 41.7 | 45.4 | - - | 46.0 | - - | - - | - - | - - |
|  | 4 | 45.0 | 44.1 | - - | - - | - - | - - | - - | - - |
|  | 5 | 48.7 | 49.6 | - - | 44.0 | - - | - - | - - | - - |
| Sept | 1 | 42.0 | 44.0 | 30.0 | - - | - - | - - | - - | - - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 45.5 | 49.5 | - - | 42.1 | - - | - - | - - | - - |
| | 3 | 40.0 | 45.0 | - - | 44.8 | - - | - - | - - | - - |
| | 4 | 37.3 | 40.2 | 37.8 | 44.4 | - - | - - | - - | - - |
| Oct | 1 | - - | - - | 36.5 | 40.0 | - - | - - | - - | - - |
| Maximum | | 53.0 | 55.2 | 46.2 | 54.6 | 54.1 | 71 | 58.5 | 75 |
| Mean | | 44.2 | 45.8 | 41.1 | 44.9 | 49.1 | - - | 53.9 | - - |

[1] Hourly mean calculated from weekly sample.

[2] Maximum 1-hr observation.

**Sulfur Dioxide**

Sulfur dioxide pollution is produced during combustion of materials (such as oil and coal) that contained reduced sulfur compounds. A variety of natural processes also produce $SO_2$, including volcanic eruptions, sea-spray, and microbial activity (Wellburn 1988). Burning of coal to produce electricity accounts for about half of the human-made emissions, with substantial contributions from refining and burning of oil. Controls on point-sources of sulfur have led to declining emission of $SO_2$ across the US; emissions have also dropped in the Southwest as a result of reduced copper smelting. The estimated emissions of $SO_2$ by state for 1990 were: 559 tons/day for Arizona, 297 tons/day for Colorado, 482 tons/day for New Mexico, and 271 tons/day for Utah (Radian 1994).

Sulfur dioxide reacts readily with water to form sulfuric acid, which may fall as “acid rain” or may react with particles to form sulfate salts. The residence time of $SO_2$ in the atmosphere is on the order of days to weeks, allowing substantial transport away from point sources before deposition as sulfuric acid or sulfate salt (Graedel and Crutzen 1989). Sulfur dioxide enters plants primarily through stomata, forming sulphite ($SO_3^{2-}$) and bisulfite ($HSO_3^-$). Although these anions are not free radicals, they are relatively reactive and can damage a variety of biochemicals either directly or after partial oxidation to form free radicals (such as sulphoxyl and superoxide radicals). Damage from $SO_2$ may include disruption of disulphide bridges that are critical in maintaining the 3-dimensional shapes of enzymes and proteins, and interference in photosynthesis (either C fixation or photophosphorylation of adenosine diphosphate (ADP) to adenosine triphosphate (ATP), Wellburn 1988). Documenting the long-term effects of $SO_2$ exposure on plants has been very difficult, owing to a variety of factors such as exposure regimes, presence of other chemicals in the air, features of controlled environment chambers, genetics of test plants, and type of response measured (visible injury, growth, etc.). Wellburn (1988) concluded that yields of agricultural crops will not be impaired at $SO_2$ levels of 60 parts per billion or less.

### *Observed Concentrations of Sulfur Dioxide (1988 - 1994)*

Sulfur dioxide concentrations have been measured as part of the sampling protocol for the IMPROVE monitoring program. The concentrations are measured for 24-hrs, twice weekly. The samples are collected on carbonate-coated filters, and then analyzed by ion chromatography in a certified laboratory. Both the maximum and the mean concentrations are given because the maximum is often many times larger than the mean and represents a few events during the year. The timing and size of peak concentrations are not correlated across the Colorado Plateau, suggesting that localized plumes do not affect all of the region. The 24-hr average concentrations of $SO_2$ were much lower than the primary standard (Table 1-8), and about two orders of magnitude below levels that are expected to affect plants. For example, the maximum observed value of 7.2 $\mu g/m^3$ (for the Grand Canyon in 1993) is less than 3 ppb, more than an order of magnitude below threshold values that may affect the most sensitive species of lichens and vascular plants (see Chapter 2).

Table 1-8. Sulfur dioxide measured by IMPROVE filter samplers ($\mu g/m^3$) (1 $\mu g/m^3$ equals approximately 0.38 parts per billion by volume).

| | Grand Canyon | | Sand Dunes | | Bryce | | Canyonlands | | Petr. For. | | Mesa Verde | | Arches | | Bandelier | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Max. | Mean | Max. | Mean | Max. | Mean | Max. | Mean | Max. | Mean | Max. | Mean | Max. | Mean | Max. | Mean |
| 88 | 3.0 | 0.6 | 0.7 | 0.2 | 0.7 | 0.2 | 0.7 | 0.5 | 2.1 | 0.6 | - - | - - | 1.5 | 0.4 | 1.9 | 0.1 |
| 89 | 2.6 | 0.4 | 0.8 | 0.2 | 1.2 | 0.3 | 3.0 | 0.5 | - - | - - | - - | - - | 2.5 | 0.6 | 1.2 | 0.2 |
| 90 | - - | - - | 3.0 | 0.3 | - - | - - | - - | - - | - - | - - | - - | - - | 3.1 | 0.4 | 1.3 | 0.2 |
| 91 | 2.8 | 0.5 | 0.6 | 0.2 | 2.2 | 0.5 | 2.3 | 0.7 | - - | - - | 2.6 | 0.4 | 1.5 | 0.4 | 1.6 | 0.1 |
| 92 | 1.7 | 0.3 | 0.0 | 0.0 | 1.4 | 0.3 | 0.8 | 0.3 | - - | - - | 5.1 | 0.9 | 1.4 | 0.4 | 0.9 | 0.2 |
| 93 | 7.2 | 0.4 | - - | - - | - - | - - | 2.9 | 0.6 | - - | - - | - - | - - | - - | - - | - - | - - |
| 94 | 2.3 | 0.3 | - - | - - | - - | - - | 1.1 | 0.5 | - - | - - | - - | - - | - - | - - | - - | - - |

24-hour samples taken twice per week

Although the mean $SO_2$ concentrations show some consistency from year to year, the maximum concentrations varied so much between 1988 and 1994 that no meaningful trend was apparent. Grand Canyon, Canyonlands, Arches, and Mesa Verde had higher maximum values, more often, than the other parks. These parks may be hit by plumes that follow the Colorado River drainage, or by more localized sources.

## Nitrogen Oxides

Molecular nitrogen ($N_2$) comprises about 78% of the atmosphere, and combustion reactions and some microbial reactions produce various oxides of nitrogen. The major oxides of nitrogen are: nitrous oxide ($N_2O$), nitrogen dioxide ($NO_2$), nitric oxide (NO), and nitric acid ($HNO_3$), and nitrate ($NO_3^-$) salt. Some N may be present as ammonia ($NH_3$) or ammonium ($NH_4^+$). Nitrous oxide is relatively unreactive (with a residence time in the atmosphere of centuries; Graedel and Crutzen 1989) and has little effect on plants, although it may play a role in generation of other N oxides and ozone.

Nitrogen dioxide and nitric oxide are often lumped together as $NO_x$, where the x denotes one or two oxygen atoms. $NO_x$ compounds are relatively reactive, with residence times of just a few days in the atmosphere. Most of the damage to plants from $NO_x$ probably derives from the conversion to nitrite ($NO_2^-$). A variety of biochemicals and processes may be affected by toxic concentrations of nitrite in cells, including photosynthesis, respiration, and photorespiration (Wellburn 1988). However, most plants in natural ecosystems are N-limited, and nitrite can be reduced to form amino-N for plant use. Levels of $NO_x$ below 300 ppb have shown no effects on plants, and most species show no effects up to 1000 ppb or higher (Wellburn 1988). Concentrations of $NO_x$ are quite low across the Colorado Plateau, representing no threat to AQRVs.

## Atmospheric Deposition

Rain water is a dilute solution of carbonic acid and salts in unpolluted areas, while rain water in polluted areas also has substantial concentrations of nitric acid ($HNO_3$) and sulfuric acid ($H_2SO_4$). The concentration of an ion, such as $H^+$, may directly affect an organism or a chemical reaction. The concentration of an ion multiplied by the total amount of precipitation water provides the quantity of an ion deposited, and this may be most important for ions such as nitrate which can act as fertilizers. In addition, some atmospheric deposition comes between precipitation events; this dry deposition includes the fall-out of particulates and deposition of gases.

The concentration of $H^+$ is commonly expressed on the pH scale, where pH is the negative of the logarithm of the $H^+$ activity (similar to concentration). A pH of 7.0 has equal quantities of $H^+$

and $OH^-$, and is considered neutral. Normal atmospheric concentrations of carbon dioxide lead to production of carbonic acid in rain water, and the normal pH for unpolluted rain may be near 5.6. The actual pH may be higher in the presence of alkaline dust particles, or lower with the presence of natural (or man-made) acids. Deposition of acid could be important from a number of perspectives. Aquatic ecosystems may be poorly buffered with respect to acidity, and input of low-pH (= high acidity) solutions may lead to high inputs of aluminum ions leached from the soil (inorganic aluminum ions are more soluble at low-pH levels) and direct damage to aquatic biota.

The deposition rates of ammonium and nitrate represent no toxic threat *per se*, but may offer the opportunity for N-deficient plants to increase growth, and perhaps shift dominance and composition of plant communities and aquatic communities. No observations or experimental information is available for the Colorado Plateau on the possible responses of plant communities to very low, chronic additions of N.

Deposition of sulfuric and nitric acid is primarily a concern for acidic soils, where movement of sulfate through the soil can lead to mobilization and transport of potentially toxic aluminum into aquatic ecosystems. In the northeastern U.S., and in some high elevation ecosystems in the west, depressions in pH and temporary loss of acid neutralizing capacity (ANC) in streams have been associated with elevated levels of nitrate. These episodes may affect native fish species and aquatic insects.

The National Atmospheric Deposition Program (NADP) was established in 1978 to document patterns in deposition across the U.S., and over time. The network currently has more than 200 sites, where uniform protocols for sampling and analysis provide comparable data by geographic regions. Precipitation samples are collected weekly at each site with an AeroChem Metrics model 301 wet/dry sampler. Personnel at each site collect water from the wet collector, and send samples to a central laboratory for analysis of major ions (sulfate, nitrate, chloride, phosphate, sodium, potassium, calcium, magnesium, ammonium, and hydrogen ion and total conductivity). Precipitation amounts at NADP sites are measured with a Belfort Model 5-780 dual-traverse recording rain gauge. The NADP protocols do not assess dry deposition rates. Estimates of dry inputs of N and S at Grand Canyon were developed as part of the National Dry Deposition Network (NDDN) for 1990 and 1991, and rates were very low (0.05 kg-N $ha^{-1}$ $yr^{-1}$ as nitrate, and 0.2 kg-S $ha^{-1}$ $yr^{-1}$ as sulfate; Clarke and Edgerton 1993).

The sites of the NADP across the Colorado Plateau show annual average pH values of 4.9 to 5.5 (Figure 1-5). These values are relatively high compared to the rest of the U.S. (Figure 1-6). The wet deposition of N is also relatively low, ranging from about 1.1 kg N $ha^{-1}$ $yr^{-1}$ at the Grand

Canyon to 2.5 kg N $ha^{-1}$ $yr^{-1}$ in parts of southern Colorado (Figures 1-7, 1-9), compared with > 6 kg N $ha^{-1}$ $yr^{-1}$ for much of the northeastern U.S. (Figures 1-8, 1-10). Fox et al. (1989) suggested that no forests would be affected by rates of N deposition between 3 and 10 kg N $ha^{-1}$ $yr^{-1}$, and we think that rates less than 3 kg N $ha^{-1}$ $yr^{-1}$ likely pose no threat to desert, shrub, or forest ecosystems. Deposition of S as sulfate is also low, ranging from 0.7 to 2.4 kg S $ha^{-1}$ $yr^{-1}$ (Figure 1-11), again much lower than for the northeastern U.S. (Figure 1-12). The current deposition rates of S probably have no effect on air quality related values, especially given the high concentrations of sulfate in the arid and semi-arid soils of the Plateau. Fox et al. (1989) suggested that deposition rate less than 3 kg S $ha^{-1}$ $yr^{-1}$ could not threaten forests even on very sensitive soils.

Critical loads of S deposition have been set by the Canadians in the range of 2.7-6.7 kg S $ha^{-1}$ $yr^{-1}$ to protect low-ANC, oligotrophic (nutrient poor) lakes and streams. The NADP maximum value of wet S in deposition on the Colorado Plateau (2.4 kg $ha^{-1}$ $yr^{-1}$) probably represents more than half of the total deposition. Accounting for both wet and dry deposition, S inputs on the Colorado Plateau probably fall below the critical range suggested for Canadian systems; additional information may be needed on dry deposition rates, however; too little direct information is available for gauging the sensitivity of unique aquatic resources such as potholes or tinajas that may be oligotrophic and low-ANC. Also, these critical loading estimates were developed for eastern aquatic systems, and are of limited value in this semi-arid environment. One study suggested that 10 kg N $ha^{-1}$ $yr^{-1}$ may be a critical load for protecting aquatic ecosystems in northern Europe (Dise and Wright 1995). Maximum loads of wet N deposition on the Colorado Plateau are 2.5 kg N $ha^{-1}$ $yr^{-1}$, (or perhaps slightly higher if dry deposition is included; Clarke and Edgerton 1993). This is notably lower than published suggestions for critical loads for affecting air quality related values, though we note again that these loads were generally developed for different types of ecosystems than those occurring over much of the Colorado Plateau.

Figure 1-6. Rainfall pH (laboratory values) for the U.S. for 1995 (map from NADP, Colorado State University).

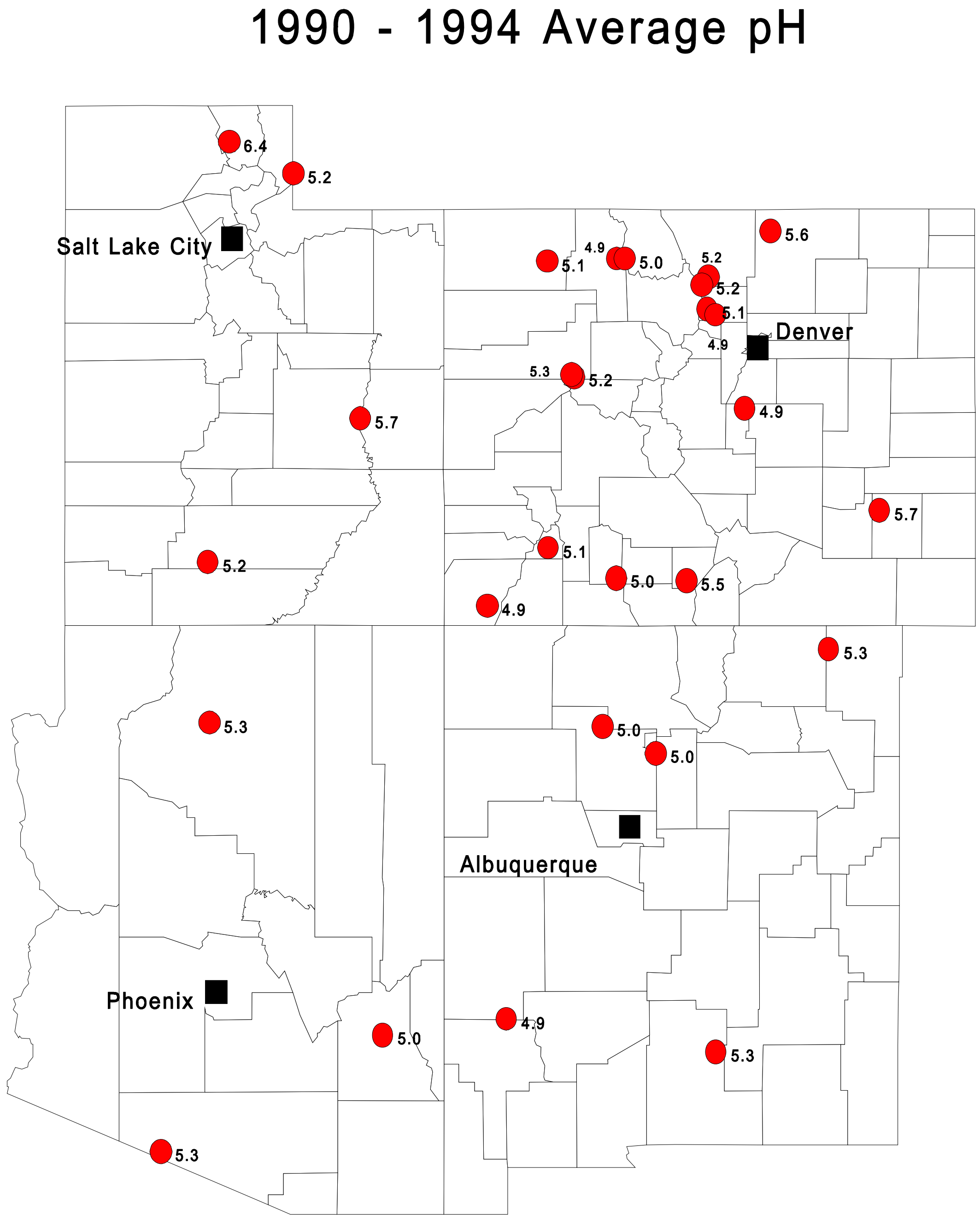


Figure 1-8. Ammonium deposition ($NH_4^+$; multiply by 0.778 for N only) for the U.S. for 1995 (map provided by NADP, Colorado State University.

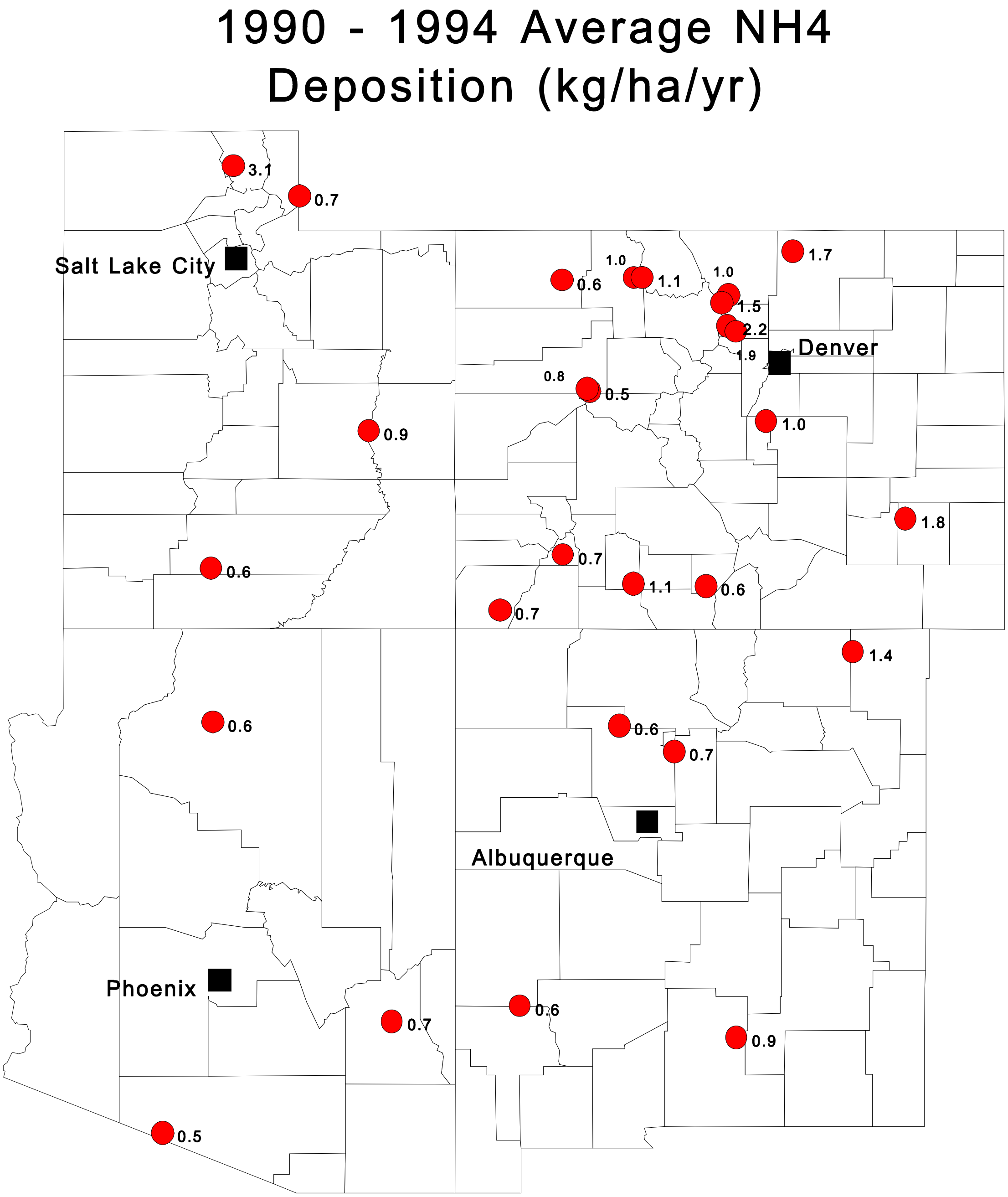


Figure 1-10. Nitrate deposition ($NO_3^-$; multiply by 0.226 for N only) for the U.S. for 1995 (map from NADP, Colorado State University.

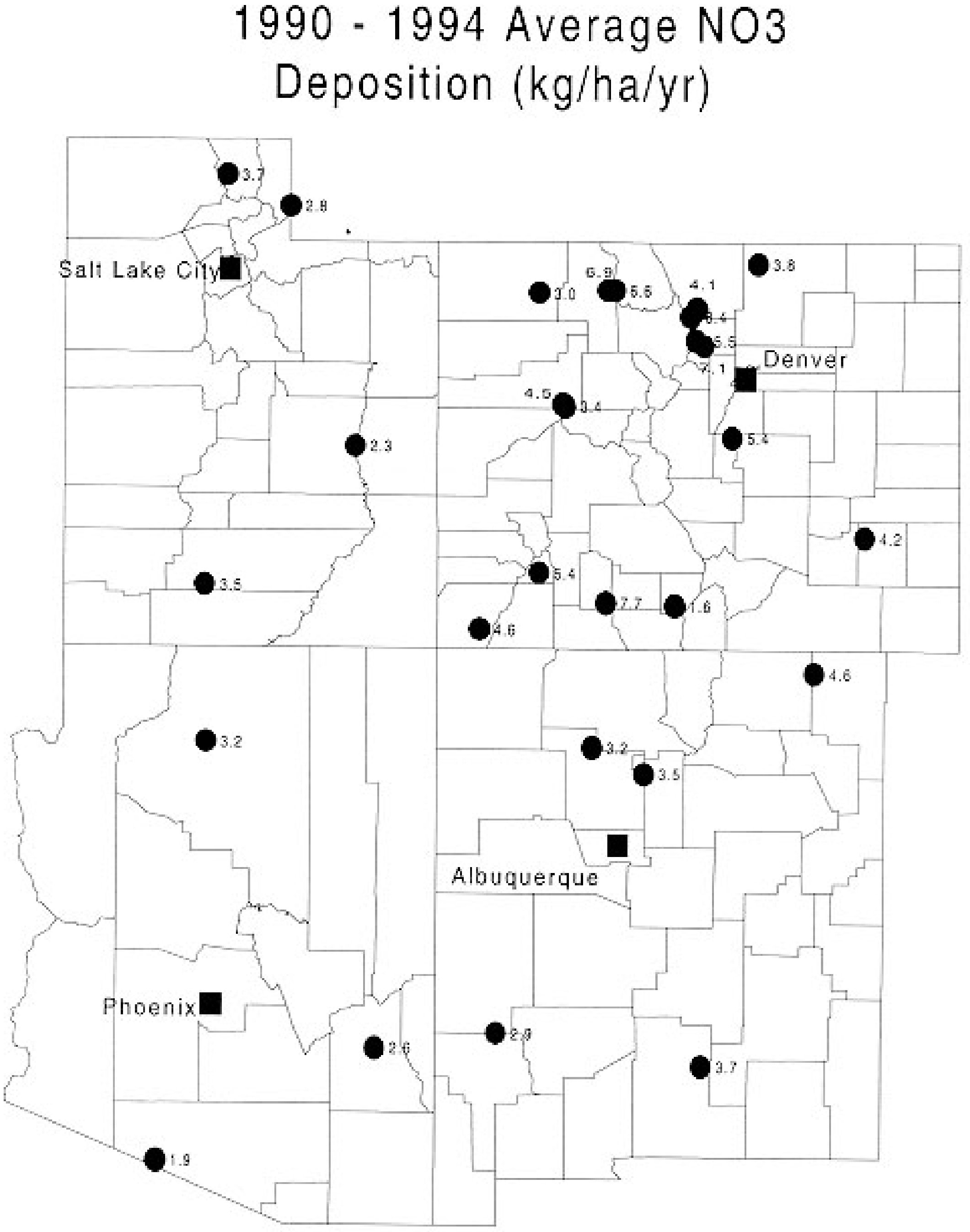
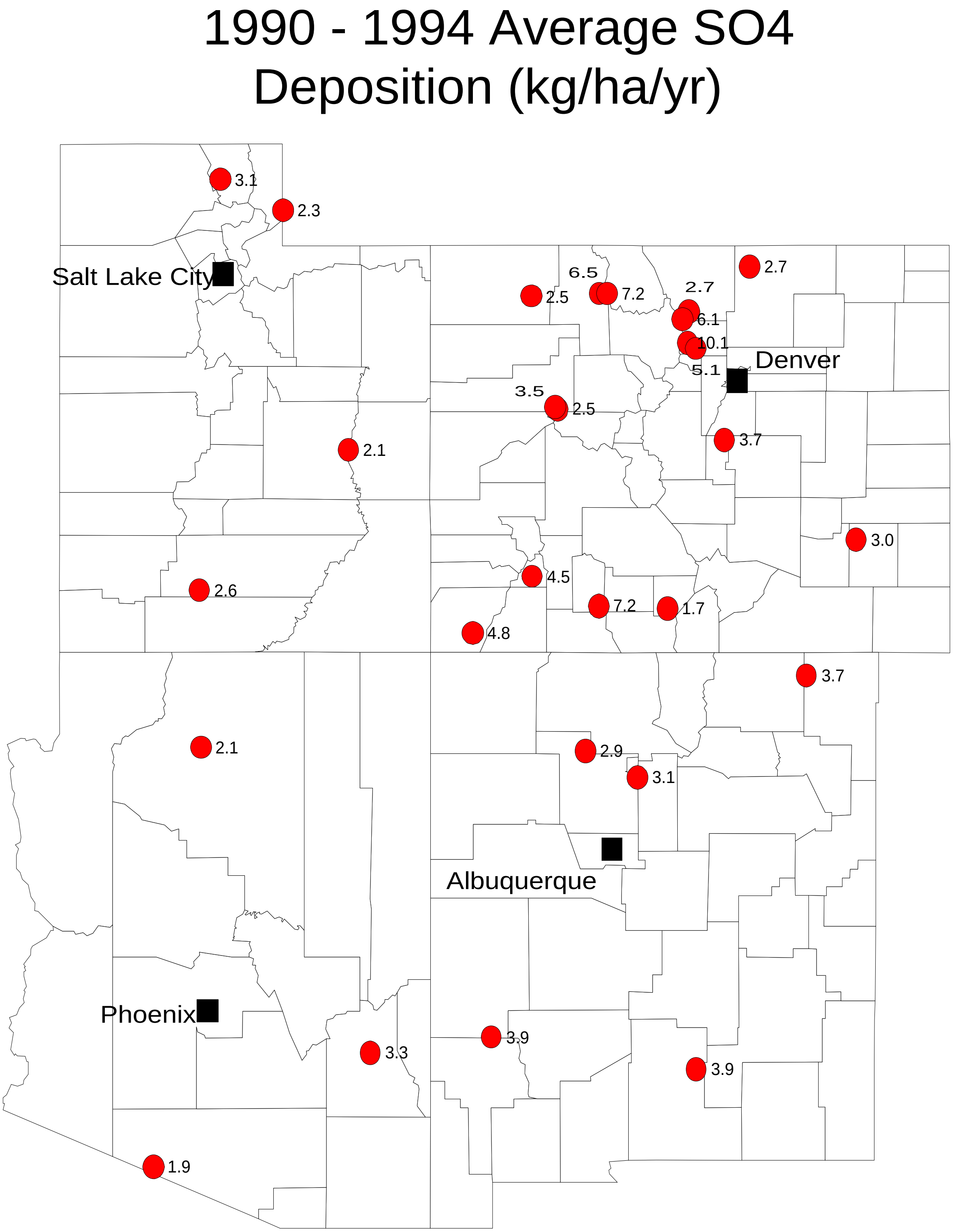


Figure 1-9. Nitrate deposition ($NO_3^-$; multiply by 0.226 for N only) for the Colorado Plateau and surrounding areas. Dots represent NADP monitoring sites, squares are major cities (data from NADP, Colorado State University).

Figure 1-12. Sulfate deposition ($SO_4^{2-}$; multiply by 0.333 for S only) for the U.S. for 1995 (map from NADP, Colorado State University).



## Other Oxidants, Toxics, Heavy Metals, Radioactive Nuclides

A wide variety of other air pollutants may affect ecological systems, including oxidants [such as PAN (peroxylacyl nitrate)], organic pesticides, heavy metals (such as cadmium), and radioactive nuclides. Almost no information is available relevant to these chemicals and AQRVs on the Colorado Plateau. The State of Arizona is conducting some monitoring of radioactive particles in the air at Grand Canyon (see Chapter 9), and the levels are too low to pose a concern. The only likely importance of any of these would involve either naturally occurring soils with high concentrations of heavy metals (such as selenium), point-source spills of contaminants, or resumption of widespread mining of uranium.

## Aquatic Systems and AQRVs

The parameters related to aquatic ecosystems include water quality, aquatic species populations (flora and fauna, both vertebrate and invertebrate), community structure, and process rates (e.g. nutrient cycling). These AQRVs can be affected by atmospheric deposition of nitrogen, sulfur, and acidity, resulting in acidification, nitrogen saturation, eutrophication, and nuisance algae blooms.

Aquatic AQRVs are usually described in broad terms, with the focus of surface water chemistry measurements on pH, ANC, and nutrients. Assessment of both chemical and biological parameters needs to consider the seasonal and interannual variability in these measurements that are due to natural variation.

Biological populations and ecosystem processes that may be affected by deposition of acidity and nutrients include:

1) phytoplankton and periphyton (especially diatoms and blue-green alga);
2) zooplankton (especially *Daphnia* species);
3) stream invertebrates (especially *Baetis* species)
4) aquatic vertebrates, including different life history stages of fish and amphibians;
5) nitrogen cycling in watershed soils and surface waters.

A summary of the possible effects of deposition on water chemistry and aquatic biota is included in the 1991 State-of-Science documents from the National Acid Precipitation Assessment

Program (NAPAP) (Baker et al. 1990, Baker et al. 1990, Thornton et al. 1990, Turner et al. 1990, Wigington et al. 1990). In our discussions of the "sensitivity" of aquatic systems on the Colorado Plateau, we are primarily concerned with the change in pH and ANC of low conductivity waters. When acid deposition falls on watersheds with bedrock that resists weathering, ANC and pH decline in the surface waters and sulfate or nitrate concentrations may rise. The organisms most likely to respond to such changes in the chemistry of surface waters include: native fish species (such as trout, dace, and minnows), aquatic insects, and amphibian larvae. The most common aquatic systems found on the Colorado Plateau are large rivers (e.g. the Colorado River) or high ANC feeder streams. Although these systems do not fall in the "sensitive" category, it is important to consider whether small, low conductivity systems might respond to increases in deposition of hydrogen, sulfur or nitrogen under increased atmospheric loading rates.

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## Chapter 2. Sensitivities of Terrestrial and Aquatic Ecosystems to Air Pollutants

Air quality impacts in National Parks and Monuments include the potential effects of pollutants on terrestrial and aquatic ecosystems. In general, impacts on terrestrial ecosystems are considered as impacts on plants because animals are generally considered to be less sensitive to most pollutants. Exceptions to this generalization may include sensitivity of wildlife species to ozone, but we found no information that would provide a basis for evaluating potential wildlife impacts (such as ozone damage) on the Colorado Plateau. Therefore, our discussion of sensitivity of ecosystems focuses on plants for terrestrial ecosystems, and on chemistry, plants and animals of aquatic ecosystems.

### Ozone

Ozone ($O_3$) is an important component of the upper atmosphere, where it forms naturally when molecular oxygen ($O_2$) absorbs ultraviolet light. This atmospheric layer of ozone in the stratosphere is crucial for absorbing potentially damaging ultraviolet radiation. In the troposphere near the ground, ozone can be produced through a variety of reactions among air pollutants, and high concentrations of ozone may harm plants and animals. Ozone forms in the lower atmosphere primarily when light splits nitrogen dioxide ($NO_2$) into nitric oxide (NO) and a single oxygen atom (O), which then combines with molecular oxygen ($O_2$) to form ozone. The presence of hydrocarbons (especially aldehydes and ketones, produced by both vegetation and combustion of fossil fuels) can accelerate ozone formation. When these hydrocarbons absorb light, they can produce free radicals (highly reactive compounds with unpaired electrons, such as peroxyl radicals) which accelerate the splitting of nitrogen dioxide. Ozone concentrations tend to be highest in the afternoon as a result of production of nitrogen dioxide and hydrocarbons earlier in the day (Wellburn 1988, Böhm 1992).

Ozone damages plants (and animals) by oxidizing important biochemicals. Ozone uptake in plants occurs primarily through open stomates, so ozone exposure is relatively low during the night or during periods of moisture stress when stomates are closed. Once inside the mesophyll of leaves, cell walls offer little resistance to diffusion of ozone. A wide variety of reactions occur once ozone enters cells. Proteins and fatty acids are attacked, leading to increased membrane permeability (and “leaking”). When ozone damage is light, membranes can be repaired and leakage of sugars, potassium and other compounds declines (Wellburn 1988). Higher levels of exposure lead to irreparable damage to a variety of cell membranes, organelles, and functions.

Visible injury to plant leaves typically include small flecks of yellow (chlorotic flecking) or purple and black that may develop into larger regions (mottling). In western conifers, needle tips tend to show chlorotic mottling first, with symptoms spreading toward the base of the needles; needles with more than 50% chlorotic mottling typically die, leading to sparsely foliated branches (Stolte et al. 1992). Species vary substantially in sensitivity to ozone, and within species some genotypes can be more susceptible than others.

The overall syndrome of ozone impacts involves many steps in plant biochemistry and ecology. Ozone may reduce the leaf area and photosynthesis of plants, lowering growth and also lowering resistance to pests and pathogens. Ozone stress typically does not kill plants, but lower carbohydrate supplies may reduce resistance to a point where pests, such as bark beetles on Jeffrey pine in southern California, substantially increase mortality rates (Miller 1992). The actual mechanisms of reduced resistance to insects and pathogens probably relate to altered carbon status of the trees, including balances between secondary compounds and other biochemicals.

Animals are also susceptible to high ozone concentrations; ozone irritates eyes and bronchial passages by disrupting cell membranes.

Ozone concentrations are typically highest near urban centers, where the precursor chemicals are produced in abundance. The half-life of ozone in the column of air in the lower atmosphere is about 2-4 weeks [Intergovernmental Panel on Climate Change (IPCC) 1994]; close to the ground, ozone is consumed even more quickly by reaction with vegetation. This half-life is short enough to insure that the highest ozone concentrations will be near the sources of nitrogen dioxide and hydrocarbon pollution, but long enough to allow elevated concentrations to move with air masses to more remote locations.

A variety of approaches have been used to characterize sensitivity of plants to ozone, including average hourly exposure, exposure to peak concentrations, and weighted average exposures where high concentration periods are weighted more heavily than low periods (Lefohn and Foley 1993). Fox et al. (1989) suggested that ozone concentrations below 35 ppb for a growing season average, or 75 ppb peak, would represent no threat to vegetation in Class I areas. The range of possible impacts for the most sensitive species was thought to begin somewhere between 35 and 55 ppb for growing season averages, with peaks up to 110 ppb. Beyond these levels, sensitive plants should develop signs of injury.

Heck and Cowling (in press) summarized consensus from a workshop that was held to define critical levels of ozone for impacts on plants. For natural ecosystems, this group concluded that foliar injury may be the best indicator of ozone damage; additional information would focus on levels of ozone that would result in reduced tree growth in natural forests or plantations. The workshop participants concluded that the best measure of ozone exposure would combine both concentration and duration of exposure; the “sum60" value multiplies the ozone concentration in excess of 60 ppb by the number of hours, for a period of 12 hrs/day summed over 90 days of the growing season. This index may be viewed as a “threshold weighting” index rather than an index that would weight periods of higher concentrations more heavily (Musselman et al. 1995). Foliar injury should be prevented if the “sum60" exposure remained below 8000 to 12000 ppb-hrs., and growth impacts should be prevented if exposures remained below 10000 to 16000 ppb-hrs. Exposures above this level may represent a potential threat to sensitive species, although less-sensitive species may be susceptible only to much higher exposures.

As mentioned in Chapter 1, the EPA is proposing a revised secondary standard for ozone concentrations to protect plants. The criteria document (EPA 1996) recommends a much higher threshold for the secondary standard than Heck and Cowling (in press); the secondary standard would be set at 25000 to 38000 ppb-hrs (for 12 hrs/day and a 90-day season).

The cumulative ozone exposures on the Colorado Plateau (Chapter 1) commonly fall within the range suggested by Heck and Cowling (in press) as leading to foliar injury on sensitive species, and some years at some locations fall into the range where they suggest sensitive species may show growth reductions. In contrast, only one year (1991) at one area (Bandelier) exceeded the secondary standard of 25000 ppb-hrs suggested by the EPA staff paper (EPA 1996).

The applicability of the current and proposed ozone standards to conditions on the Colorado Plateau may be problematic. The semi-arid nature of the landscape leads to prolonged periods where many plants will have closed stomata, reducing the uptake of ozone. We expect that actually doses of ozone experienced by plants on the Colorado Plateau will generally be lower than those experienced by plants in wetter regions at equivalent exposures to atmospheric concentrations.

The sensitivity of plants can be examined with controlled fumigation studies, with the exposure characterized by the peak concentration (such as the 120 ppb standard) or by cumulative, chronic exposure (such as the Sum60 index or similar threshold approaches). These controlled studies need to be supplemented by field studies that search for characteristic signs of chlorotic flecking (stippling) and mottling from ozone exposure.

No reports of visible injury or growth reduction from ozone (or other pollutants) have been registered for the Colorado Plateau. This absence of evidence could result from an absence of impact, or from the paucity of direct examinations.

In the absence of evidence of injury, inferences about the potential sensitivity of species on the Colorado Plateau to ozone can be based on controlled exposure studies. Unfortunately, only a few of the major species from the Colorado Plateau have been tested in controlled experiments for sensitivity to ozone. We surveyed the literature for available information on controlled exposure experiments for species that occur in one or more of the NPS Class I areas of the Colorado Plateau. Tables 2-1 (trees and shrubs) and 2-2 (forbs and grasses) summarize this information, rating species as sensitive or not-sensitive for 3 levels of peak ozone exposure. Species were rated as “sensitive” if they showed any response to a given level of ozone exposure, including visible foliar injury or growth rate. The occurrence of species in each park or monument was based on NPFlora listing. Any species that did not show sensitivities in studies at 120 ppb or lower are probably relatively resistant to ozone effects at ambient concentrations on the Colorado Plateau. Species that demonstrated some sensitivity at 120 ppb or lower are discussed in more detail below.

Controlled exposure experiments have a variety of challenges for determining ozone sensitivity of plants (Pye 1988), including:

- developing a proper “control” treatment; use of ambient air may include a significant exposure to ozone, but use of charcoal-filtered air introduces other artifacts;
- developing a realistic exposure profile, including peak concentrations, diurnal and seasonal variation, length of exposure period;
- environmental conditions (particularly supply of water and nutrients);
- size and age of the plants (particularly important for trees); and
- selection of response variables to be measured, such as gas exchange or biomass.

Based on the available literature, only a few tree species are potentially sensitive to peak ozone concentrations of < 120 ppb (Table 2-1). The major tree species on the Colorado Plateau that appears sensitive to ozone is aspen (*Populus tremuloides*).

Table 2-1. Reported sensitivity of tree and shrub species to ozone. N = not sensitive, X = sensitive by some measure, and blanks indicate no reported information. Species is absent (0) or present (1) in the park or monument.

| | | | | Ozone (ppb) range N=not sensitive X=sensitive | | | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | | | | | | | | | | | | References |
| *Abies concolor* | (Gord. & Glend.) Lindl. | Pinaceae | white fir | N | N | N/X | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | Davis & Wilhour 1976; Davis & Wood 1972; Miller & Millecan 1971; Miller et al. 1983; Treshow & Stewart 1973; Bytnerowicz & Grulke 1992 |
| *Acacia greggii* | Gray | Fabaceae | catclaw acacia | N | N | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Temple 1989 |
| *Acer grandidentatum* | Nutt. | Aceraceae | bigtooth maple | | | N | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | Davis & Wilhour 1976; Treshow & Stewart 1973 |
| *Acer negundo* | L. | Aceraceae | boxelder | | | N/X | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | Davis & Wilhour 1976; Treshow & Stewart 1973 |
| *Amelanchier alnifolia* | Nutt. | Rosaceae | serviceberry | X | X | X | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Davis & Wilhour 1976; Mavity et al. 1995; Treshow & Stewart 1973 |
| *Arctostaphylos uva-ursi* | (L.) Spreng. | Ericaceae | red bearberry | | | X | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Tingey et al. 1976a |
| *Artemisia tridentata* | Nutt. | Asteraceae | big sagebrush | | N | X | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Davis & Wilhour 1976; Treshow & Stewart 1973; |
| *Artemisia sp.* | | Asteraceae | | X | | | | | | | | | | | | | | Mavity et al. 1995 |
| *Cercis canadensis* | | Fabaceae | redbud | | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Wood & Coppolino 1971 |
| *Chilopsis linearis* | (Cav.) Sweet | Bignoniaceaea | desert willow | N | N | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Temple 1989 |
| *Gleditsia triacanthos* | L. | Fabaceae | honey-locust | | | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Davis & Wilhour 1976; Treshow 1970; Wood & Coppolino 1971 |
| *Mahonia repens* | G.Don | Berberidaceae | Oregon grape | | | N | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | Davis & Wilhour 1976; Treshow & Stewart 1973; |
| *Physocarpus monogynus* | | Rosaceae | mountain ninebark | X | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | Mavity et al. 1995 |
| *Picea pungens* | Engelm. | Pinaceae | blue spruce | | | X | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | Davis & Wilhour 1976; Treshow 1970 |
| *Picea engelmannii* | Parry ex Engelm. | Pinaceae | Engelmann spruce | N | | | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | Bytnerowicz & Grulke 1992 |

| Table 2-1 continued | | | | Ozone (ppb) N=not sensitive X=sensitive | | | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | | | | | | | | | | | | References |
| *Pinus ponderosa var scopulorum* | Engelm. | Pinaceae | ponderosa pine | | | X | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Aitken et al. 1984 |
| *Pinus ponderosa var ponderosa* | Laws. | Pinaceae | ponderosa pine | N | X | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Benes et al. 1995; Beyers et al. 1992; Bytnerowicz et al. 1989; Bytnerowicz et al. 1990; Bytnerowicz & Grulke 1992; Davis 1977; Evans & Miller 1972; Fenn et al. 1995; Miller et al. 1963, 1969, 1983; Peterson & Arbaugh 1988; Pye 1988; Richards et al. 1968; Temple et el. 1992, 1993; Temple & Miller 1994; Tingey et al. 1976a,b |
| *Populus tremuloides* | Michx. | Salicaceae | quaking aspen | X | X | X | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | Berrang et al. 1986, 1991; Coleman et al. 1995a,b; Davis & Wilhour 1976; Greitner et al. 1994; Karnosky 1976; Karnosky & Witter 1992; Pell et al. 1995; Pye 1988; Treshow 1970; Treshow & Stewart 1973; Wang et al. 1986 |
| *Potentilla fruticosa* | L. | Rosaceae | golden hardhack | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Prunus virginiana* | | Rosaceae | choke cherry | X | | | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | Mavity et al. 1995 |
| *Pseudotsuga menziesii* | (Mirb.) Franco | Pinaceae | Douglas-fir | N/X | N | N/X | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Davis & Wood 1972; Gorissen et al. 1994; Gorissen et al. 1991a,b; Gorissen & Van Veen 1988; Martin et al. 1988; Pye 1988; Smeulders et al. 1995; Wilhour & Neely 1977; Bytnerowicz & Grulke 1992 |
| *Quercus gambelii* | Nutt. | Fagaceae | Gambel oak | | N | X | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Rhus trilobata* | Nutt. ex T. & G. | Anacardiaceae | squawberry | X | X | | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | Temple 1989 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rosa woodsii* | Lindl. | Rosaceae | Woods' rose | | N | X | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Davis & Wilhour 1976; Treshow & Stewart 1973 |

Table 2-1, continued

| Species | Authority | Family | Common name | Ozone (ppb)<br>N=not sensitive<br>X=sensitive<br>0-120 | 121-200 | >200 | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rubus parviflorus* | | Rosaceae | thimbleberry | X/N | X/N | | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Mavity et al. 1995; Hogsett (unpubl) |
| *Sambucus racemosa* | | Caprifoliaceae | red berried elder | N | N | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | Mavity et al. 1995; Hogsett (unpubl); Brace et al. (unpubl) |
| *Salix gooddingii* | Ball. | Salicaceae | Goodding's willow | N | X | | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | Temple 1989 |
| *Toxicodendron radicans* | (L.) Kuntze | Anacardiaceae | eastern poison ivy | | N | X | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | Davis & Wilhour 1976; Treshow & Stewart 1973; |
| *Vaccinium sp.* | | | | X | | | | | | | | | | | | | | Mavity et al. 1995 |

### *Aspen*

Most studies of ozone exposure on aspen have found that aspen is more sensitive than most tree species, with effects developing with peak exposures of < 120 ppb. Ozone effects on photosynthesis and growth of aspen occur below concentrations required to produce chlorotic flecking or mottling on leaves. W. Hogsett (unpublished data) found that biomass of aspen seedlings was reduced by about 10% for ozone exposures totaling 5000 to 55,000 ppb-hour per year by the Sum60 criteria (12 hr/day for 92 days), with a strong effect of genotype. A 30% loss of growth developed between levels of cumulative exposure of 15,000 ppb-hr and 70,000 ppb-hr. Based on these Sum60 values, some loss of aspen growth may be occurring in Class I areas of the Colorado Plateau, although most varieties tested were from the Great Lakes region.

Coleman et al. (1995a,b) exposed 3 clones of aspen to 3 levels of ozone in open-topped chambers. The ozone levels included charcoal filtered air (maximum peak concentration of 34 ppb), an “ambient” treatment representing conditions in the Great Lakes region (where peak concentrations exceed 70 ppb), and twice ambient (peak values over 140 ppb). Over the 2-year study, exposure to ambient ozone lowered the growth (biomass) of the most sensitive clone by about 40%, with little effect on the 2 less-sensitive clones. At twice ambient ozone, growth of the most-sensitive clone declined slightly below the ambient treatment; the intermediate clone declined by about 25% relative to the charcoal-filter treatment, and the least sensitive clone appeared to decline in whole-plant photosynthesis but not in growth.

Greitner et al. (1994) examined the effects of ozone exposure in relation to drought stress and N supply. The ozone exposures included a control of charcoal filtered air (with ozone concentrations of about 25 to 35 ppb), and an “ambient” treatment to mimic Pennsylvania conditions of about 80 ppb ozone. Exposure to the 80 ppb treatment reduced seedling carbon gain (which should index growth) by about 20 to 30% regardless of water treatment or N treatment.

Karnosky (1976) exposed cuttings of aspen clones to various levels of ozone; 3 of the 5 clones showed some visible injury to leaves when exposed to levels of ozone as low as 50 ppb, and a fourth clone showed injury at 100 ppb. In a more recent study, Karnosky and Witter (1992) found that ozone exposure of 80 ppb produced visible injury to leaves, but no effect on seedling growth; fertilization with N substantially increased growth regardless of ozone exposure.

Pell et al. (1995) also found that N supply strongly affected the sensitivity of aspen to ozone exposures of about 75 ppb; stresses from too little to too much N prevented any injury from ozone, whereas seedlings with adequate N supply showed less growth when exposed to ozone.

Wang et al. (1986) performed an ozone exposure experiment for 3 years with aspen saplings in open topped chambers. One set of chambers received only charcoal filtered air, and the other ambient air with peak concentrations exceeding 120 ppb between 1 and 6 times each year (mean hourly values averaged about 60 ppb for the growing seasons). Sapling growth was reduced by about 12 to 24%, depending on the sensitivity of the clones. Only one of the 5 clones tested showed visible injury to leaves, even though all clones showed reduced growth with exposure to ambient ozone.

We conclude that evidence from ozone exposure studies indicates that aspen injury by ozone is possible under current ozone concentrations on the Colorado Plateau. No reports have been made of visible injury to leaves, nor of any unexpected growth reductions. This absence of evidence of any ozone impacts may indicate no impacts occur, but the lack of extensive study on the Colorado Plateau leaves open the possibility of unrecorded impacts.

### *Douglas-fir*

The evidence for ozone sensitivity of Douglas-fir is more mixed than for aspen. A series of carbon dioxide ($^{14}CO_2$) experiments by Gorissen et al. (1991a, 1991b, 1994) and Smeulders et al. (1995) documented variable sensitivity of Douglas-fir seedlings and trees in the Netherlands to levels of ozone exposure from 50 to 120 ppb. These studies documented some effects on patterns of carbohydrate transport and storage (some gas exchange effects from their earlier studies could not be repeated in their later studies at the lowest ozone level), but were not designed to look for overall growth effects. No visible injury on foliage was found. Bytnerowicz and Grulke (1992) report unpublished results of N. Grulke on exposure of Douglas-fir, ponderosa pine, Engelmann spruce and white fir to 60-70 ppb ozone; no effects of ozone were found for any of the species. W. Hogsett (unpublished data) found that a 10% growth reduction in Douglas-fir required a Sum60 (12 hr/day for 92 days) exposure of 60,000 ppb-hr to 250,000 ppb-hr, which is far higher than current exposures for the Colorado Plateau. Ozone exposure studies indicate a possibility of physiologic effects on Douglas-fir below 120 ppb (perhaps as low as 60 ppb), but no substantial effects have been shown, and no reports of visible injury or growth reductions exist for the Colorado Plateau or for areas that are much more polluted.

### *Ponderosa Pine*

Many studies have examined the sensitivity of ponderosa pine (and closely related Jeffrey pine) in the San Bernardino Mountains and Sierra Nevada of California. As early as the 1950s, chlorotic mottling was observed on ponderosa pine, and the condition was dubbed the "x-disease" (Miller 1992). Controlled exposure to ozone in the 1960s demonstrated that ozone caused the observed injury; mean ozone concentrations near Los Angeles in the 1970s were averaging near 100 ppb, with frequent peaks above 250 ppb. Many controlled exposure studies demonstrated sensitivity to high concentrations of ozone (> 200 ppb), such as Miller et al. (1983). High mortality of pines resulted from beetle attacks and root rot pathogens on ozone-injured trees. Farther north where ozone concentrations are lower (but still exceeding 100 ppb for 30 days or more), ponderosa pine with visible foliar injury show reduced growth (by an average of about 10%) relative to more resistant genotypes that show no injury (Peterson and Arbaugh 1992). However, Peterson and Arbaugh (1992) found no evidence of widespread growth reductions in recent decades.

Ozone concentrations are somewhat lower along the Front Range in Colorado, and no foliar injury on ponderosa pine (or other conifers) has been reported (Graybill et al.1992). The Rocky Mountain variety of ponderosa pine (var. *scopulorum*) may be less sensitive to ozone than the coastal subspecies (var. *ponderosa*). For example, Aitken et al. (1984) found that exposure of 2-yr-old seedlings of var. *scopulorum* to 250 ppb produced no visible injury, which is much higher than levels found to affect the coastal subspecies. However, we know of no exposure studies that compared the subspecies in the same experiment, so differences in protocols may account for some of the apparent differences in sensitivity.

No major growth changes are evident for forests of the Front Range, although a few of the stands examined by Graybill and by Peterson and Arbaugh could be interpreted as having some unusual growth declines at some point in recent decades. In southern Arizona, Graybill and Rose (1992) reported some anomalously low growth rates in several of the ponderosa pine stands they examined. They suggested that the absence of growth rings and reduction in width of growth rings could reflect stand dynamics associated with the aging of stands that were established in the wet period of 1900 to 1920, or could result from some air-borne pollutant. No visible injury was observed by Graybill and Rose (1992).

W. Hogsett (unpublished data) found that a 10% growth reduction for ponderosa pine may develop with cumulative ozone exposures (Sum60 with 12 hr/day for 92 days) of 15,000 ppb-hr to 55,000 ppb-hr. Both the Grand Canyon and Bandelier have experienced levels overlapping the lower end of this range. The evidence is strong that ponderosa pine in southern California have been affected by regional levels of ozone, but no evidence of any impact is available for the Colorado Plateau.

### *Shrubs*

Much less work has focused on the potential effects of ozone on shrubs than on trees (Table 2-1). Temple (1989) exposed a variety of species in Joshua Tree National Park to levels of ozone from about 50 to 200 ppb, and also conducted some comparisons of plant performance in ambient- and charcoal-filtered air in Riverside, California. Squawbush (*Rhus trilobata*) was the most sensitive species, showing no visible injury at 50 ppb, slight injury at 100 ppb, and greater than 10% foliar injury at 150 ppb and above. Shrubs grown in charcoal filtered air had no sign of visible injury, but they also grew less than plants exposed to the full ambient level of ozone (about 75 ppb) in Riverside. Temple (1989) concluded that *Rhus trilobata* may be a useful species for indicating ozone levels; foliar injury might appear at levels near 100 ppb, even though the plants may show no growth decline (or even an increase) at these levels.

Research reported in an unpublished report from the USDA Forest Service Center for Forest Environmental Studies (Mavity et al. 1995) sought to find shrub species that might be sensitive indicators of ozone pollution in the West. A variety of species were exposed in a chamber for about a month to three levels of ozone: low = average of 25 ppb (50 ppb maximum), medium = average of 55 ppb (80 ppb maximum), and high = average of 75 ppb (120 ppb maximum). These shrub seedlings were relatively small, with weights of < 10 g, and heights of <10 cm, so extrapolation of the results to juvenile and mature shrubs is problematic. The results of these investigations are described below.

Ninebark (*Physocarpus monogynus*) was relatively sensitive to ozone; the average leaf weight/shrub declined by 25% from the low to the moderate ozone exposure, and stem weight declined by about 15% (which was not statistically significant). About a third of the individuals exposed to the medium ozone level showed some defoliation, brown necrosis and red stippling of leaves (but little chlorotic mottling).

Choke cherry (*Prunus virginiana*) was less sensitive to ozone exposure, showing no effect of the medium level on plant weight, and only moderate stippling, necrosis and mottling of some leaves.

Serviceberry (*Amelanchier alnifolia*) appeared to decrease in photosynthesis rates with the medium ozone exposure, although the effect was not statistically significant. Stem weight was not affected by ozone exposure, although leaf drop increased substantially at the high ozone level. Mavity et al. (1995) concluded that *Amelanchier* would not be a useful indicator of ozone exposure levels because of only minor development of visible symptoms. Brace et al. (unpublished manuscript) exposed *Amelanchier alnifolia* seedlings to 60 days of ozone (with 126 ppb daily peaks and 20 ppb nightly minima), and found stippling on older foliage followed later by necrotic spots. Further work may be needed to determine the usefulness of *Amelanchier* as an indicator of ozone exposure.

Mavity et al. (1995) also exposed seedlings of *Artemisia* shrubs, but they didn't mention which species of *Artemisia* was used. Photosynthesis and plant growth were both reduced at the medium ozone level; plants exposed to the medium level produced only about 75% the biomass of those in the low ozone treatment. The major foliar symptom of ozone exposure was a curling of leaves, which Mavity et al. (1995) concluded would not be specific enough for use as an indicator of in-field ozone exposure.

Thimbleberry (*Rubus parviflorus*) shrubs were tested in two sets of exposures, one for small seedlings (< 1 g stem weight), and another for slightly larger individuals (up to 6 g stem weight). The smaller seedlings were very sensitive to the medium ozone exposure, producing just half the stem weight of the seedlings in the low-ozone treatment. The smaller seedlings also showed a variety of visible injuries, but the authors concluded the symptoms may not be specific enough to ozone injury to have promise as a bioindicator. The larger seedlings showed essentially no response to ozone treatment, except perhaps an increase in growth at the medium ozone level. No visible injury developed on the larger seedlings. This comparison of small and somewhat larger seedlings underscores the importance of differences in sensitivity with either life stage of development, or experimental protocols.

An unidentified species of elderberry (*Sambucus*) was also tested and found to show no response to ozone, with the exception of some chlorotic mottling at the highest ozone level. An unidentified species of *Vaccinium* showed no response to ozone in terms of photosynthesis or growth, although the foliage did develop classic purple stippling. Mavity et al. (1995) concluded that *Vaccinium* species may have substantial promise for use as an indicator species, and they recommended more trials.

No evidence of visible injury or growth effects has been reported for field-grown shrubs in the Colorado Plateau. Some controlled-exposure evidence indicates a potential for moderate sensitivity of some shrubs to moderate level of ozone, with sensitivity described as signs of visible injury or changes in growth of very young seedlings.

### *Grasses, Sedges, Forbs*

Even less information is available on the ozone-sensitivity of non-woody vegetation on the Colorado Plateau (Table 2-2). Treshow and Stewart (1973) exposed over 70 species of common plants in the Intermountain West to concentrations of 150 ppb or higher by placing chambers over well-established plants in the field. Only a few species were affected at the minimum ozone level, and this minimum level was far greater than any concentrations of ozone that apply to the Colorado Plateau. Thompson et al. (1984) exposed 47 species of annual plants in the Mojave desert to 50 ppb or greater levels of ozone. A few species that are also present on the Colorado Plateau that were sensitive (based on visible injury) to exposures lower than 120 ppb were: *Camissonia claviformis, Cryptantha nevadensis, Malacothrix glabrata, Mentzelia albicaulis, Pectocarya heterocarpa* and *Pectocarya platycarpa*. Bytnerowicz et al. (1988) also tested the sensitivity of desert annuals to ozone. Only three species were sensitive to ozone (at levels of 120 ppb and above): *Camissonia claviformis, Camissonia hirtella*, and *Erodium cicutarium*; each of these species showed 1 to 3% injury to leaves, whether irrigated or not irrigated.

We conclude that no evidence currently indicates that species of grasses, sedges, or forbs show much sensitivity to ozone levels below 100 or 120 ppb. No reports of visible injury or other effects are available for the Class I NPS areas of the Colorado Plateau.

Table 2-2. Reported sensitivity of forbs, sedges, and grasses to ozone. N = not sensitive, X = sensitive by some measure, and blanks indicate no reported information. Species is absent (0) or present (1) in the park or monument.

| | | | | Ozone (ppb) range<br>N=not sensitive<br>X=sensitive | | | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | | | | | | | | | | | | References |
| *Achillea millefolium* | L. | Asteraceae | common yarrow | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | Treshow & Stewart 1973 |
| *Agastache urticifolia* | (Benth.) Kuntze | Lamiaceae | nettle leaf giant hyssop | | X | X | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Allium acuminatum* | Hook. | Liliaceae | taper tip onion | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Ambrosia psilostachya* | DC. | Asteraceae | western ragweed | | N | N | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Angelica pinnata* | S.Wats. | Apiaceae | small leaf angelica | | N | X | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Baileya pleniradiata* | | Asteraceae | woolly desert marigold | N | | N | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Thompson et al. 1984 |
| *Bromus carinatus* | Hook. & Arn. | Poaceae | California brome | | N | X | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Bromus rubens* | | Poaceae | foxtail brome | N | | X | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | Thompson et al. 1984 |
| *Bromus tectorum* | L. | Poaceae | cheat grass | | X | X | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Treshow & Stewart 1973 |
| *Calochortus nuttallii* | Torr. | Liliaceae | sego lily | | N | N | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Camissonia claviformis* | (Torr. & Frem.) Raven | Onagraceae | brown eyes | X | X | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Carex siccata* | Dewey | Cyperaceae | | | N | X | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Caulanthus cooperi* | | Brassicaceae | Cooper's wild cabbage | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Chaenactis fremontii* | | Asteraceae | morning bride | N | | X | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Chaenactis stevioides* | | Asteraceae | broad-flower pincushion | N | N | X | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Chenopodium fremontii* | Wats. | Chenopodiaceae | Fremont's goosefoot | | N | X | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Treshow & Stewart 1973 |
| *Chorizanthe brevicornus* | | Polygonaceae | brittle spine flower | N | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Cichorium intybus* | L. | Asteraceae | chicory | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |

Table 2-2 continued

| | | | | Ozone (ppb) range<br>N=not sensitive<br>X=sensitive | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
| *Cirsium arvense* | (L.) Scop. | Asteraceae | Canadian thistle | | N | X | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Collomia linearis* | Nutt. | Polemoniaceae | narrowleaf mountain trumpet | | N | X | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Conium maculatum* | L. | Apiaceae | poison hemlock | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Cryptantha angustifolia* | | Boraginaceae | panamint cat's eye | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Cryptantha circumscissa* | | Boraginaceae | cushion cat's eye | N | | X | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Cryptantha micrantha* | | Boraginaceae | red root cat's eye | N | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Thompson et al. 1984 |
| *Cryptantha nevadensis* | | Boraginaceae | Nevada cat's eye | X | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Cryptantha pterocarya* | | Boraginaceae | wing-nut cat's eye | N | N | X | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Descurainia californica* | (Gray) O.E.Schultz | Brassicaceae | Sierran tansy mustard | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Descurainia pinnata* | | Brassicaceae | western tansy mustard | N | | X | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | Thompson et al. 1984 |
| *Epilobium augustifolium* | L. | Onagraceae | fireweed | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Erodium cicutarium* | | Geraniaceae | red-stem stork's bill | N/X | X | X | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Eucrypta micrantha* | | Hydrophyllaceae | dainty desert hideseed | N | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Festuca octoflora* | | Poaceae | 8flower 6weeks grass | N | N | N | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Galium bifolium* | Wats. | Rubiaceae | twin leaf bedstraw | | N | X | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Gayophytum racemosum* | T. & G. | Onagraceae | black foot groundsmoke | | N | X | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Gentiana amarella* | L. | Gentianaceae | autumn dwarf gentian | | X | X | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |

Table 2-2 continued

| | | | | Ozone (ppb) range<br>N=not sensitive<br>X=sensitive | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
| *Geranium fremontii* | Torr. | Geraniaceae | purple cluster crane's bill | | N | X | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Geranium richardsonii* | Fisch. & Traut. | Geraniaceae | white crane's bill | | X | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Hedysarum boreale* | Nutt. | Fabaceae | boreal sweet vetch | | X | X | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Helianthus annuus* | L. | Asteraceae | common sunflower | | N | X | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Treshow & Stewart 1973 |
| *Juncus sp.* | | | | | N | X | | | | | | | | | | | | Treshow & Stewart 1973 |
| *Langloisia schottii* | | Polemoniaceae | Schott's calico | N | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Lathyrus lanszwertii* | Kell. | Fabaceae | Nevada vetchling | | N | X | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Lathyrus pauciflorus* | Fern. | Fabaceae | few flower vetchling | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Lepidium lasiocarpum* | | Brassicaceae | hairy-pod pepperwort | N | | N | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Thompson et al. 1984 |
| *Lolium perenne* | L. | Poaceae | perennial rye grass | | X | | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | Nussbaum et al. 1995 |
| *Lupinus concinnus* | | Fabaceae | | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Lupinus sp.* | | Fabaceae | | | | X | | | | | | | | | | | | Tingey et al. 1976a |
| *Malacothrix glabrata* | | Asteraceae | smooth desert dandelion | X | | X | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Medicago sativa* | L. | Fabaceae | alfalfa | | N/X | X | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Hill et al. 1961; Treshow 1970; Treshow & Stewart 1973 |
| *Mentzelia albicaulis* | | Loasaceae | white stem blazingstar | X | | X | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Thompson et al. 1984 |
| *Mertensia arizonica* | Greene | Boraginaceae | aspen bluebells | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Mimulus guttatus* | DC. | Scrophulariaceae | seep monkey | | N | X | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |

flower

Table 2-2 continued

| Species | Authority | Family | Common name | Ozone (ppb) range N=not sensitive X=sensitive 0-120 | 121-200 | >200 | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Osmorhiza occidentalis* | Torr. | Apiaceae | sierran sweet cicely | | N | X | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Treshow & Stewart 1973 |
| *Pectocarya heterocarpa* | | Boraginaceae | chuckwalla combseed | X | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Pectocarya platycarpa* | | Boraginaceae | broad fruit combseed | X | | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Perityle emoryi* | | Asteraceae | emory's rockdaisy | N | | N | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Phacelia heterophylla* | Pursh | Hydrophyllaceae | variable leaf scorpion weed | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Plantago insularis* | | Plantaginaceae | blond plantain | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Poa annua* | L. | Poaceae | annual bluegrass | | N | X | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Hill et al. 1961 |
| *Poa pratensis* | L. | Poaceae | Kentucky blue grass | | N | X | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | Treshow & Stewart 1973 |
| *Polemonium foliosissimum* | A.Gray | Polemoniaceae | towering jacob's ladder | | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Polygonum douglasii* | Greene | Polygonaceae | | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Rumex crispus* | L. | Polygonaceae | curly dock | | N | X | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Salvia columbariae* | | Lamiaceae | California sage | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Sphaeralcea ambigua* | | Malvaceae | apricot globe mallow | N | | N | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | Thompson et al. 1984 |
| *Stephanomeria exigua* | | Asteraceae | white plume wire lettuce | N | | X | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | Thompson et al. 1984 |
| *Streptanthella longirostris* | | Brassicaceae | long beak fiddle mustard | N | | X | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | Thompson et al. 1984 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Taraxacum officinale* | Wiggers | Asteraceae | common dandelion | | N | X | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Treshow & Stewart 1973 |

Table 2-2 continued

| | | | | Ozone (ppb) range N=not sensitive X=sensitive | | | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Authority | Family | Common name | 0-120 | 121-200 | >200 | | | | | | | | | | | | References |
| *Thalictrum fendleri* | Engelm. | Ranunculaceae | Fendler's meadow rue | | N | X | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Thysanocarpus curvipes* | | Brassicaceae | sand fringepod | N | N | X | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Bytnerowicz et al. 1988; Thompson et al. 1984 |
| *Trifolium repens* | L. | Fabaceae | white clover | X | X | X | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | Blum et al. 1982; Cooley & Manning 1987; Karlsson et al. 1995; Letchworth & Blum 1977; Nussbaum et al. 1995; Reich & Amundson 1985 |
| *Urtica gracilis* | Ait. | Urticaceae | stinging nettle | | N | X | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Treshow & Stewart 1973 |
| *Veronica anagallis-aquatica* | L. | Scrophulariaceae | blue water speedwell | | N | X | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |
| *Vicia americana* | Muhl. | Fabaceae | American purple vetch | | N | N/X | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | Treshow & Stewart 1973 |
| *Viguiera deltoidea* | | Asteraceae | triangle goldeneye | N | | N | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Thompson et al. 1984 |
| *Viola adunca* | Sm. | Violaceae | hook spur violet | | N | X | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Treshow & Stewart 1973 |

### *Lichens*

Surprisingly little work has been done on the sensitivity of lichens to ozone. Lichens are generally regarded as sensitive indicators of air pollution because they lack stomates and are more tightly coupled to the atmosphere (Nash and Wirth 1988). Patterns of lichen abundance around point sources of pollution have pointed to non-ozone pollutants, particularly $SO_2$, as the major agent damaging lichens. For example, McCune (1988) examined the patterns of lichen abundance with distance from Indianapolis, Indiana, and found that lichen patterns correlated relatively well with gradients of $SO_2$ concentrations but not with ozone concentrations. A few studies have fumigated lichens with ozone. Eversman and Sigel (1987) reported that fumigation with just 30 ppb of ozone reduced photosynthesis of some lichens; however, it is not clear that their “no ozone” level would have acheived lower ozone concentrations given that background levels are usually higher than this level (particularly in eastern Tennessee). Other fumigation studies, such as the one by Nash and Sigal (1979), exposed lichens to concentrations of ozone that were far higher than ambient conditions (such as 500 ppb), providing no insights for field conditions. We found only one study that used realistic levels of ozone fumigation. Scheidegger and Schroeter (1995) exposed several species (including *Hypogymnia bitteri*, which occurs in Bandelier NM) to 40 ppb ozone at night and 90 ppb ozone in the day, and found 4% to 40% reductions in chlorophyll concentrations relative to the control treatment. Indirect evidence of lichen sensitivity to ozone comes from Sigal and Nash (1983) who transplanted *Hypogymnia enteromorpha* into “clean” and “high ozone” areas of the Los Angeles basin, and the lichens in the high ozone area had greater degradation of the thalli.

Peterson et al. (1992) developed a list of California lichens that are sensitive to various levels of ozone exposure, from < 20 ppb (growing season 7-hr mean) to >70, and these sensitivity ratings were used by Eilers et al. (1994) to infer lichen sensitivity for Class I NPS areas of the Pacific Northwest. These ratings are inferred from patterns of lichen distribution in the Los Angeles Basin, and an assumption that ozone is the primary factor controlling lichen distribution. In the absence of experimental exposures of lichens to ozone, there is no basis for judging the likely validity of these assumptions. It is also difficult to see how species that are sensitive to concentrations of less than 20 ppb could have evolved given that pre-industrial concentrations of ozone were likely higher than this (EPA 1996).

## Sulfur Dioxide

### *Trees and Shrubs*

Trees are generally thought to be insensitive to ambient concentrations of sulfur dioxide. Most experiments with controlled exposures of tree seedlings to $SO_2$ used concentrations that were far too high to be interpretable for field conditions (e.g. Davis and Wilhour 1976). Ponderosa and pinyon pines are the only tree species from the Colorado Plateau that have been included in fumigation studies. Leininger (1991) reported that 60 days of exposure to 35 ppb $SO_2$ reduced needle weight and diameter of ponderosa pine seedings. Kärenlampi and Houpis (1986) found that fumigation with 75 ppb of $SO_2$ caused browning of needle tips. Some other studies have found less effect; Hogsett et al. (1989) found variable effects of $SO_2$ fumigation on measures of plant growth for ponderosa pine, including stimulation of bud elongation by levels of $SO_2$ on the order of 30 ppb. Trujillo et al. (1993) exposed pinyon pine seeds, germinants, and 1-yr-old seedlings to $SO_2$. Their minimum level was 200 ppb, which is 2 orders of magnitude or more beyond ambient levels in pinyon pine's range; however, no effects were seen on growth or biomass unless extremely severe exposures of 3000 ppb or higher were used.

All of the pine studies used concentrations of $SO_2$ that are many times higher than levels found on the Colorado Plateau, so we conclude there is no cause for concern about direct effects of $SO_2$ exposure on plants in this area.

Table 2-3. Reported sensitivity of vascular plants and lichens to $SO_2$. N = not sensitive, X = sensitive by some measure. Species is absent (0) or present (1) in the park or monument.

| Species | Authority | Family | Common name | $SO_2$ at <50ppb N= not sensitive X = sensitive | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Grasses, forbs, trees* | | | | | | | | | | | | | | | | |
| *Agropyron smithii* | Rydb. | Poaceae | western wheatgrass | X | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | Lauenroth et al. 1985 |
| *Agropyron spicatum* | | Poaceae | | N | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Runeckles et al. 1981 |
| *Lolium perenne* | L. | Poaceae | perennial rye grass | N | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | Runeckles et al. 1981 |
| *Pinus edulis* | Engelm. | Pinaceae | pinyon pine | N | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Trujillo et al. 1993 |
| *Pinus ponderosa* | Laws. | Pinaceae | ponderosa pine | X/N | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Leininger 1991;Kärenlampi & Houpis 1986; Hogsett et al. 1989 |
| *Pseudotsuga menziesii* | (Mirb.) Franco | Pinaceae | Douglas-fir | X/N | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | Gorrisen & Van Veen 1988; Runeckles et al. 1981 |
| *Lichen Species* | | | | | | | | | | | | | | | | |
| *Buellia sp.* | | | | X | 0 | 1 | 0 | | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Vick & Bevan 1976 |
| *Buellia alboatra* | (Hoffm.) Brauth and Rostr. | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970; Wetmore 1983 |
| *Buellia punctata* | (Hoffm.) Mass. | | | X/N | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983; Will-Wolf 1980 |
| *Caloplaca aurantiaca* | | | | X | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970 |
| *Caloplaca cerina* | (Ehrh. ex Hedwig) Th. Fr. | | | X | 0 | 0 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Hawksworth & Rose 1970; Wetmore 1983 |
| *Candelaria concolor* | (Dicks.) Stein | | | X/N | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970; Wetmore 1983; Will-Wolf 1980; Johnson 1979 |
| *Candelariella vitellina* | (Ehrh.) Mull. | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Wetmore 1983 |
| *Candelariella* | (Ach.) Lettau. | | | X | 0 | 0 | 0 | | 0 | 1 | 1 | 0 | 0 | 0 | 1 | Wetmore 1983 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *xanthostigma* | | | | | | | | | | | | | | | | |
| *Cladonia sp.* | | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Vick & Bevan 1976 |

Table 2-3, continued.

| *Lichens* | Authority | Family | Common name | SO$_2$ at < 50 ppb<br>N = not sensitive<br>X = sensitive | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cladonia balfourii* | | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 1 | 0 | 1 | Johnson 1979 |
| *Cladonia chlorophaea* | | | | X | 0 | 0 | 0 | | 0 | 1 | 1 | 0 | 0 | 0 | 1 | Johnson 1979 |
| *Cladonia coniocraea* | auct. (fide Ahti) | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Wetmore 1983 |
| *Cladonia fimbriata* | (L.) Fr. | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Wetmore 1983 |
| *Collema tenax* | (Sw.) Ach. | | | X | 1 | 1 | 0 | | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Sheridan 1979 |
| *Hypogymnia physodes* | (L.) Nyl. | | | X/N | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970; Holopainen & Karenlampi 1984; Johnsen & Sochting 1973; Rose & Hawksworth 1981; Vick & Bevan 1976; Johnson 1979 |
| *Lecanora carpinea* | (L.) Vainio | | | X | 0 | 0 | 0 | | 0 | 1 | 0 | 0 | 1 | 0 | 0 | Johnsen & Sochting 1973 |
| *Lecanora chlarotera* | Nyl. | | | X | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970; Wetmore 1983 |
| *Lecanora dispersa* | (Pers.) Sommerf. | | | N | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 1 | 1 | 1 | LeBlanc & Rao 1973; Vick & Bevan 1976; Wetmore 1983 |
| *Lecanora hagenii* | (Ach.) Ach. | | | N/X | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Wetmore 1983; Johnson 1979 |
| *Lecanora muralis* | (Schreber) Rabenh. | | | N | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Vick & Bevan 1976; Wetmore 1983 |
| *Lecanora saligna* | (Schr.) Zahlbr. | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Wetmore 1983 |
| *Lecidea sp.* | | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Sheridan 1979 |
| *Lepraria incana* | (L.) Ach. | | | X/N | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983 |
| *Lobaria scrobiculata* | | | | X | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970 |
| *Pannaria sp.* | | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970 |
| *Parmelia sp.* | | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Vick & Bevan 1976 |
| *Parmelia olivacea* | | | | X | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Wetmore 1983 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Parmelia subargentifera* | Nyl. | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Wetmore 1983 |

Table 2-3, continued.

| *Lichens* | Authority | Family | Common name | SO$_2$ at < 50 ppb N = not sensitive X = sensitive | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Parmelia sulcata* | Tayl. | | | X/N | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970; LeBlanc & Rao 1973; Rose & Hawksworth 1981; Will-Wolf 1980; Von Arb & Brungold 1990; Von Arb et al. 1990; Johnson 1979 |
| *Phaeophyscia orbicularis* | (Necker) Moberg | | | X | 1 | 1 | 0 | | 0 | 0 | 1 | 1 | 1 | 0 | 1 | Wetmore 1983 |
| *Physcia adscendens* | (Fr.) H. Olivier. | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983 |
| *Physcia aipolia* | (Ehrh.) Hampe | | | X | 0 | 1 | 1 | | 0 | 0 | 1 | 1 | 0 | 0 | 1 | Hawksworth & Rose 1970; Wetmore 1983 |
| *Physcia dubia* | (Hoffm.) Lett. | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Johnsen & Sochting 1973 |
| *Physcia orbicularis* | (Neck.) Poetsch | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970; Johnsen & Sochting 1973 |
| *Physcia stellaris* | (L.) Nyl. | | | N/X | 0 | 1 | 1 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Beekley & Hoffman 1981; Wetmore 1983 |
| *Physcia tenella* | | | | X | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Wetmore 1983 |
| *Physconia detersa* | | | | X | 0 | 0 | 0 | | 0 | 0 | 1 | 1 | 1 | 1 | 1 | Wetmore 1983 |
| *Physconia grisea* | (Lam.) Poelt | | | N/X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 1 | Beekley & Hoffman 1981; Hawksworth & Rose 1970; Johnson 1979 |
| *Physconia pulverulenta* | (schreb.) Poelt. | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970 |
| *Ramalina calicaris* | | | | X | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970 |
| *Ramalina obtusata* | (Arn.) Bitt. | | | X | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | Hawksworth & Rose 1970; Wetmore 1983 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Ramalina pollinaria* | | | | X | 0 | 1 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970 |
| *Rhizoplaca melanophthalma* | (Ram.) Leuck. & Poelt. | | | X | 1 | 1 | 0 | | 1 | 1 | 1 | 0 | 1 | 1 | 1 | Belnap & Harper 1990 |

Table 2-3, continued.

| *Lichens* | Authority | Family | Common name | $SO_2$ at < 50 ppb<br>N = not sensitive<br>X = sensitive | ARCH | BAND | BLCA | BRCA | CANY | CARE | GRCA | GRSA | MEVE | PEFO | ZION | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Usnea sp.* | | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Vick & Bevan 1976 |
| *Usnea florida* | | | | X | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Hawksworth & Rose 1970; Wetmore 1983 |
| *Usnea hirta* | (L.) Weber ex Wigg. | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 0 | Eversman 1978; Wetmore 1983; Johnson 1979 |
| *Usnea subfloridana* | Stirton | | | X | 0 | 1 | 0 | | 0 | 0 | 1 | 0 | 1 | 0 | 1 | Hawksworth & Rose 1970; Rose & Hawksworth 1981; Wetmore 1983 |
| *Xanthoria candelaria* | (L.) Th. Fr. | | | X | 0 | 0 | 0 | | 0 | 0 | 1 | 0 | 0 | 1 | 0 | Hawksworth & Rose 1970; Johnson 1979 |
| *Xanthoria elegans* | (Link) Th. Fr. | | | N | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 1 | 1 | Vick & Bevan 1976 |
| *Xanthoria fallax* | (Hepp) Arn. | | | N/X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Beekley & Hoffman 1981; Wetmore 1983; Will-Wolf 1980 |
| *Xanthoria polycarpa* | (Hoffm.) Rieber | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Hawksworth & Rose 1970; Rope & Pearson 1990; Wetmore 1983 |

### *Grasses and Forbs*

The pattern for tree experiments appears to extend to grasses and forbs. Some studies used $SO_2$ concentrations that greatly exceed ambient levels (200 ppb $SO_2$ or higher; Thompson et al. 1984) and concluded that some species were indeed sensitive to extremely high levels of $SO_2$ pollution. Other studies used much lower rates of fumigation. For example, Lauenroth et al. (1985) used a gradient of average $SO_2$ exposure from 10 to 60 ppb (with peaks as high as 100 to 800 ppb). *Agropyron smithii* was not sensitive to the lowest level of $SO_2$ tested, and sensitivity to higher levels depended on level of defoliation (used to simulate grazing).

### *Lichens and Microbiotic Crusts*

As mentioned above, many people expect that lichens are sensitive indicators of $SO_2$ pollution. However, this universal expectation has rarely been backed up by strong proof of a direct mechanism of damage (Farmer et al. 1992). Many studies used unrealistically high concentrations of $SO_2$ (e.g. Nash 1973). We found many cases where lichens were determined to be sensitive to levels of $SO_2$ below 50 ppb (Table 2-3), but we found no cases that demonstrated sensitivity to levels as low as those that characterize the Colorado Plateau. The report that claimed the greatest sensitivity of lichens to $SO_2$ was one by Johnson (1979) who related the occurrence of lichen within Seattle to $SO_2$ concentrations. Areas with average $SO_2$ concentrations of just 3 ppb (and peaks of 30 ppb) had lower lichen diversity than areas with higher concentrations. However, no other covariates that may have played a role in determining lichen distribution were considered. In any case, the concentrations of $SO_2$ in the Colorado Plateau are substantially below even this minimum level for Seattle, so it is highly unlikely that any $SO_2$ impacts on lichens occur.

Weber (undated report) concluded that lichens were unlikely to be useful in monitoring air pollution in Bandelier NM because the dominant lichen forms present are crustose lichens growing on rocks (which are less sensitive to pollution than fruticose lichens growing on trees) and the occurrence of fruticose lichens is so sporadic and rare as to prevent useful observations.

Belnap et al. (submitted) examined the sensitivities of S deposition along a presumed deposition gradient around the Navaho Power Plant near Page, Arizona. They sampled lichens at distances of 6, 12, 21, 42, and 225 km from the plant. No measurements of $SO_2$ exposure or S deposition were included, and water-extractable sulfate of the 0-6 cm depth soil showed no pattern with distance from the plant. The rock lichens *Lecanora argopholis, Xanthoparmelia taractica,* and *Rhizoplaca* *melanophthalma* showed greater chlorophyll degradation at 12 km from the plant than at other distances. Leakage of electrolytes from lichens tended to be much higher at the 6 and 12 km distances than at farther distances. No effects were apparent on rock lichens at 21 km or beyond. Conversely, cyanobacterial crusts (dominated by *Microcoleus vaginatus*) showed least chlorophyll degradation at the 12 km site; nitrogen fixing activity of *Collema tenax* (a soil lichen) was higher at 42 and 225 km than at closer distances. Unfortunately, the experiment had no replication of sites (all samples for each distance were taken from one location), so any differences in lichen condition among study sites could result from distance from the power plant or from other difference among sites unrelated to the power plant.

Most of the National Parks of the Colorado Plateau have substantial areas covered by microbiotic crusts. These crusts are assemblages of lichens, algae, moss, cyanobacteria, fungi and bacteria, which form continuous cover with relief of 1 to several cm. The crusts have been referred to as cryptogamic, cryptobiotic, microphytic, and other names. Key features of these crusts include stabilization against wind erosion by virtue of gluing soil particles together (primarily by cyanobacterial filaments; Williams et al. 1995a,b), and symbiotic N fixation. The crusts are very sensitive to trampling by animals, hikers, and vehicles (including mountain bikes), and some concerns have been raised about the potential sensitivity of the crusts to air pollution (cf. St. Clair et al. 1993). Belnap et al. (unpublished MS) examined the sensitivities of crusts and lichens to deposition in a series of experiments. They exposed crusts (from both sandstone and limestone substrates) containing *Microcoleus vaginatus* to a range of pH rainfall, from 3.5 to 6.5 (1:1 sulfuric acid:nitric acid), and found that chlorophyll content *increased* with declining pH. No evidence indicates any unusual sensitivity of microbiotic crusts to air pollution.

## Sensitivity of Aquatic Ecosystems

### *Acidification*

In discussions of surface water chemistry, we refer to the "sensitivity" of stream water to chemical change. This sensitivity can be gauged as the acid-neutralizing capacity (ANC; typically measured as $10^{-6}$ mol of charge/L, = $\mu mol_c$/L = $\mu$eq/L), or the ability of the stream water to buffer incoming acids. When acid deposition falls on stream watersheds, located on bedrock that is resistant to weathering, the result can be a decrease in the ANC and pH in the stream water.

Depending on the chemistry of the deposition and chemistry of watershed soils there may also be increases in sulfate, nitrate, and aluminum (leached by acids from soils and sediments).

The chemistry of bedrock and soils of the Colorado Plateau, along with the relatively high buffering capacity of waters, generally results in aquatic ecosystems that are unlikely to acidify due to wet and dry deposition (Turk and Spahr 1991). Surface waters of the Colorado Plateau were not included in the national assessment of the status of sensitive water bodies to acid deposition carried out under NAPAP (National Surface Water Survey, Charles 1991). The preliminary mapping of the potentially susceptible surface waters was assembled by Omernik and Powers (1982) based on the ANC of fresh waters. Fresh waters with an ANC of less than 100 μeq/l were considered potentially sensitive to acid deposition; below 50 μeq/L ANC waters were considered to be extremely sensitive. Chemical changes in surface waters can affect biological populations. The organisms most likely to respond to changes in the chemistry of surface waters include: native fish species, aquatic insects or insects with aquatic larvae, and zooplankton. The three most important water chemistry factors affecting the response of species are hydrogen ion (pH), calcium, and aluminum (Baker et al. 1990).

Phytoplankton are single-celled algae that are free-floating in lakes and ponds and provide a food source for higher organisms (e.g. zooplankton) in aquatic systems. Phytoplankton species can be affected by changes in surface-water chemistry, especially by changes in pH in the range of 5-6. In general, the abundance and species richness of phytoplankton are affected by acidity, with acidic lakes having fewer species than similarly-situated lakes with circumneutral pH (Almer et al. 1974). However, there is no general trend in phytoplankton production with changes in pH due to the fact that populations of acid-tolerant algal species increase as pH drops. Insect taxa differ greatly in their response to acidity. Mayflies (Ephemeroptera) are quite sensitive, while stoneflies (Plecoptera) and caddisflies (Trichoptera) show a greater variability in response (Baker and Christensen 1991). Amphipods, mollusks, and crustaceans also decline in lakes and streams with lowered pH.

Some evidence indicates that amphibian life history stages in eastern U.S. waters have been adversely affected by acid deposition. In the Rocky Mountain region the only experimental dose-response information for amphibian effects due to episodic acidification comes from the Harte and Hoffman (1989) study of tiger salamanders (*Ambystoma tigrinum*). In low-ANC waters on the western slope of the Rockies, salamander eggs had an lethal-dose-50 (LD-50) pH of 5.6, a value observed in these high-elevation ponds during snowmelt runoff. A more recent set of lab experiments showed that competition between larval forms of *Ambystoma tigrinum* and *Pseudacris* *trisertiata* (chrous frog) (species found on the western slope of the Rockies) can be affected at pH levels of 6.0 or lower (Kiesecker, 1996).

Chronic Versus Episodic Acidification

In the early 1980s, researchers were primarily interested in the process of chronic acidification of lakes and streams caused by added sulfate from wet and dry deposition (Turner et al. 1990). This process occurs when the ANC of the streams is lost over the long-term and the pH drops as a consequence of the addition of sulfuric acid to watersheds. Deposition of sulfate to sensitive watersheds results in leaching of base cations from soils, soil acidification, and surface water acidification. This occurs as the $H^+$ in deposition replaces base cations on the soil exchange complex, and these nutrient cations then leach into aquatic systems in company with sulfate anions. In some watershed soils, particularly those studied in the southeastern U.S., sulfate in rain is adsorbed in soils until the soils are saturated. Then the sulfate begins to leach out into the stream waters, resulting in "delayed" acidification of streams (Church et al. 1992).

In the mid-1980s, researchers began to investigate the temporary acidification of streams due to large rain and snowmelt events, known as episodic acidification (Wigington et al. 1990, 1996). Studies focused on short-term changes in ANC, pH, and aluminum in stream water and attempted to relate the chemical changes to fish responses. These studies also began to focus attention on the role of nitrate in episodic acidification. In this situation, large rain storms lead to large increases in nitrate in stream water. This process seems to be the result of both atmospheric deposition of nitrate and loss of nitrate from the watershed vegetation and soils. Examples of episodic acidification are found in the eastern U.S. (Webb et al. 1995). In the western U.S., episodes of lowered pH and ANC have been detected under ice cover in lakes found at high elevations in the Rockies and Sierra Nevada (Turk and Spahr 1991; Stoddard 1995).

The closest region to the Colorado Plateau classified as sensitive under the NAPAP surface water assessment is the southern Rocky Mountains. As noted above, the chemistry of bedrock and soils of the Colorado Plateau, along with the relatively high buffering capacity of waters, results in aquatic ecosystems that are not likely to become acidified due to deposition in the wet or dry forms.

In parks of the Colorado Plateau the only aquatic systems that need to be evaluated for sensitivity to deposition inputs, either of acids or nutrients, are small rock pools (known as tinajas for longer lived pools connected during rain events or potholes for isolated ephemeral pools not part of a drainage system) and headwater streams that receive most of their input water from rainfall (Graham 1991). These water bodies do support diverse communities of organisms (Dodson 1991), which could be affected by inputs of acids or nutrients. However, even in these situations the sediments found in rock pools are likely to buffer an extremely acidic rainfall event.

### *Nitrogen Saturation*

Nitrogen saturation of watersheds is becoming more of a concern because of loadings of nitrate and ammonium in precipitation. Nitrogen saturation is defined as the state where an ecosystem can retain no additional N, and inputs match outputs (Brown et al. 1988). Some other scientists bend the definition of the word “saturation” to mean a condition when outputs rise above 0, regardless of the size of the inputs (EPA 1995). Excessive N inputs can lead to leaching of nitrate into surface waters, which in turn can affect nitrogen chemistry in surface waters, eutrophication, and, possibly, episodic and chronic acidification (Stoddard 1994).

Evidence for substantial leaching of nitrate has accumulated from a variety of sources across North America and Europe (Aber et al. 1989, Johnson and Lindberg 1992). In streams monitored in the northeastern U.S. and in the mid-Appalachian Highlands, nitrate is now observed at high concentrations during hydrologic episodes and during baseflow periods. There are a number of explanations for this nitrogen loss, including the maturation of forests (low rates of biomass accumulation in older forests may reduce the ecosystem’s ability to retain N), effects of insect infestation, and excess nitrogen supply in deposition.

There is evidence that nitrogen deposition in rain, snow, and dry fall has caused small, chronic losses of ANC in high-elevation lakes in the West. The EPA's Western Lake Survey detected measurable amounts of nitrate in lakes found in northwestern Wyoming and the Colorado Rockies (especially in Front Range locations). These concentrations are high enough to indicate that some high elevation watersheds have little remaining capacity to absorb nitrogen in deposition (EPA 1995). Because there are no baseline records, these inferences depend heavily on an assumption that nitrate leaching from watersheds would not occur in the absence of elevated deposition from the atmosphere, which remains highly debatable.

The EPA Acid Deposition Standards Feasibility Study (EPA 1995) included modelling efforts focused on sensitive surface waters in the eastern United States, ecosystems that have been extensively studied and that are known to be affected by deposition of nitrogen, sulfur, and acidity. No attempt was made to model the effects of nitrogen deposition on watersheds and surface waters of the Colorado Plateau. Most of the terrestrial ecosystems of the Colorado Plateau are probably nitrogen-limited, but many important research questions remain. The effects of current or future rates of N deposition on plant communities remains largely unexplored, as do the potential side effects on water quality and biological populations of aquatic ecosystems on the Plateau.

### *Eutrophication*

The addition of nutrients (primarily nitrogen and phosphorus) to surface waters can stimulate algal blooms and growth of submerged vegetation, leading to wide swings in oxygen availability in waters and losses of aquatic fauna (Laws 1993). The eutrophication of shallow areas of Chesapeake Bay is an example of cultural eutrophication that can be traced, in part, to atmospheric deposition of nitrogen (EPA 1994). Most of the evidence to date on the effects of deposition of nitrogen on water bodies had been reported for estuarine systems, where nitrogen, rather than phosphorus, is often the limiting nutrient. Other adverse impacts of eutrophication include loss of water clarity and aesthetic qualities of freshwater bodies and odor.

### *Conclusions on Regional N and S Deposition*

Current rates of N and S deposition on the Colorado Plateau are very low compared to other regions of the U.S. and Europe, where much of the concern about acidification, N saturation, and eutrophication developed. Most of the Class I NPS Areas of the Colorado Plateau have soils that are unlikely to be acidified easily by N or S (Binkley 1992). Most of the ecosystems are probably N limited, and may respond with increased growth if N deposition rates rise substantially. The ecosystems in the region that may be most sensitive to atmospheric deposition are probably high alpine ecosystems, where the lack of soil development or easily weathered rock may allow deposited N and S to reach aquatic ecosystems with little buffering by terrestrial ecosystems. This possibility warrants experimentation, although it is outside the Class I NPS Areas of the Colorado Plateau.

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# Chapter 3. Arches National Park

## Introduction

Arches National Monument was established in 1929 under the "Preservation of American Antiquities Act" of 1908. The enabling legislation stated:

> "these areas contain extraordinary examples of wind erosion in the form of gigantic arches, natural bridges, 'windows', spires, balanced rocks and other unique wind-worn sandstone formations, the preservation of which is desirable because of their educational and scenic value".

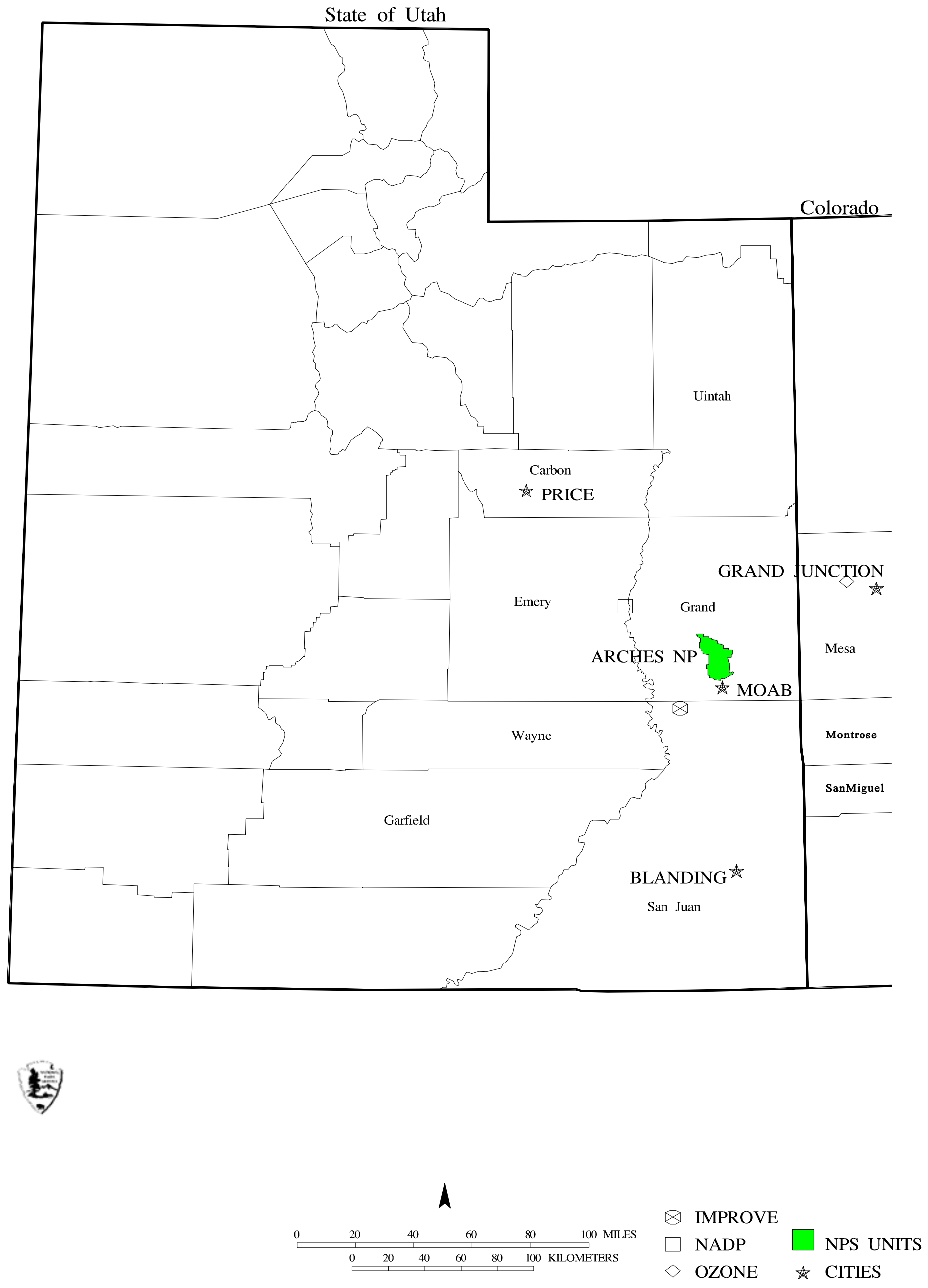
The Monument became a National Park in 1971 and today comprises 29,708 ha. About 90% of the Park is federally owned, and the remainder owned by the State of Utah and Grand County.

Arches National Park is in the high desert of southeastern Utah, with elevations ranging from 1200 m to 1725 m (Figure 3-1). The Park contains the largest concentration of natural rock arches in the world, with over 200 arches and 2000 catalogued natural openings, as well as many spectacular pink and red rock sandstone canyons, fins, slickrock terraces, towering monoliths and arches in varying stages of formation or collapse. The most well recognized formations include Landscape Arch, which spans over 91 m, Turret Arch and Delicate Arch. The Park contains many archeological features such as prehistoric pictographs and petroglyphs; the remains of at least four Native American cultures (the Archaic People, the Anasazi, the Freemont and the Utes); and the historical legacy of some of the earliest pioneer attempts to ranch and mine on the Colorado Plateau.

### *Geology and Soils*

The geology of Arches developed from a regional collapse of horizontal layers of sedimentary rock along several northwest-trending anticlines (particularly the Salt Valley and Cache Valley anticlines). The Entrada Formation splits along these anticlines and forms many parallel joints that eventually weather into the free standing rock fins and arches. Exfoliation, chemical solution from carbonic acid in rainwater, frost wedging and water erosion weather the rock surfaces; acidic deposition should not have any significant effect on weathering of rocks in the Park (Smith and Saari 1983).

Figure 3-1. Location of Arches National Park.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

The major exposed rock formations in Arches are from the Jurassic and Triassic Periods and include the massively crossbedded Navajo Sandstone, the Entrada and Wingate Sandstones and the limestones, shales and sandstones of the Kayenta and Chinle Formations. These sedimentary rock layers were deposited under a variety of climatic conditions and depositional environments that ranged from sparsely vegetated sandy deserts to shallow seas with densely vegetated shores. Seas advanced and retreated during periods of subsidence and uplift. Climate changes were also dramatic as continental-scale mountain building altered regional weather patterns and cut off the flow of moist air from the west (Chronic 1988). The regional climate today is dry (<150 mm/yr average precipitation) and warm, and so the Park is covered by bedrock, shallow soils, and only sparse vegetation. The soils of the Park reflect the geologic parent material; most are sandy and shallow, but soils developed from marine shales tend to be finer textured and high in salts.

### *Climate*

The low precipitation (annual total about 160 mm) at Arches is relatively well distributed through the year, but the hottest months of June and July (24 $^{o}$C) have relatively low precipitation

(Figure 3-2).

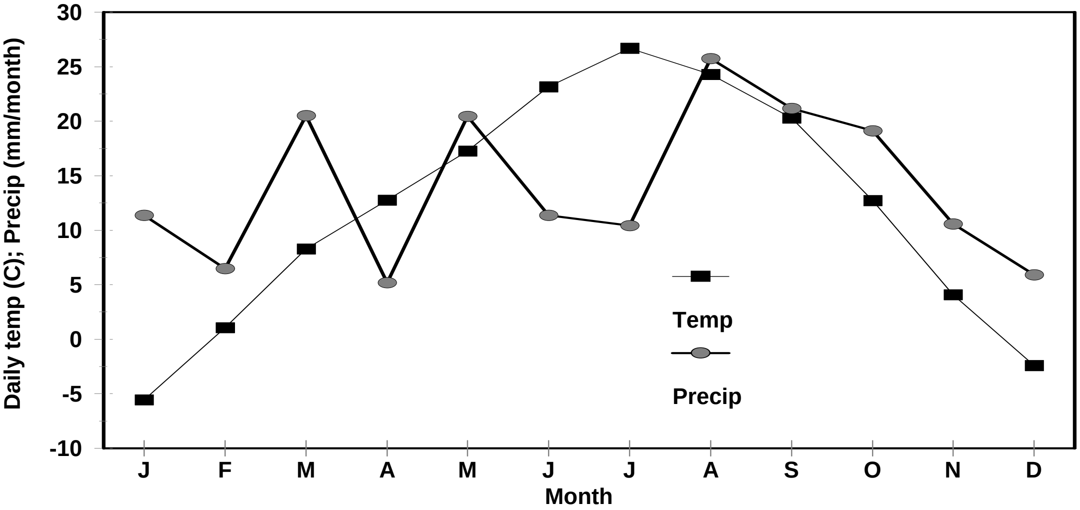
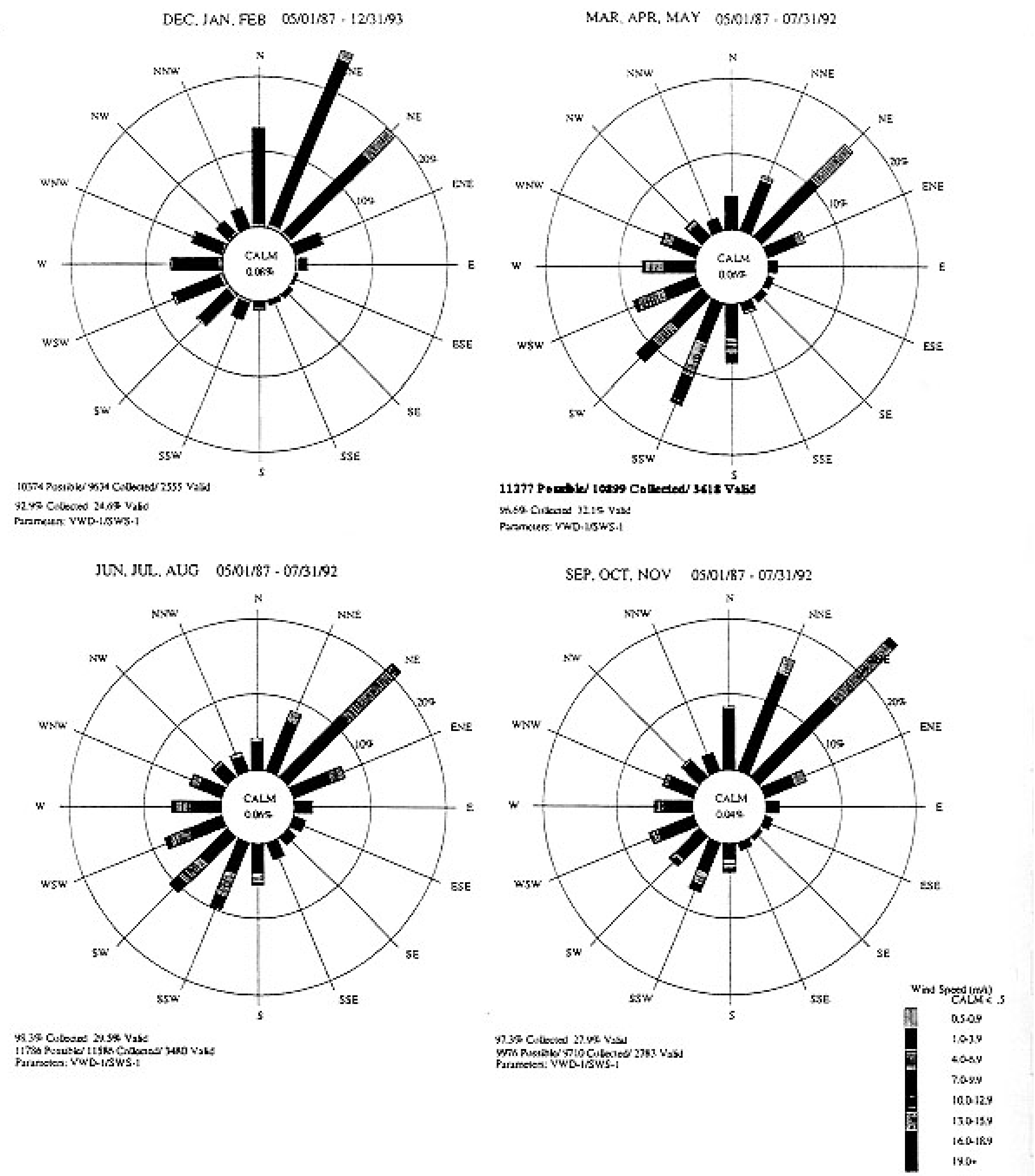


Figure 3-3. Seasonal wind roses for Arches National Park for 1987-1993.

Figure 3-3. Seasonal wind roses for Arches National Park for 1987-1993.



The prevailing wind direction for Arches is from the northeast for most seasons, with a shift towards winds from the southwest in the spring (Figure 3-3). Throughout the year, air masses moving in from the southwest have a higher velocity than the prevailing northeasterly winds.

### *Vegetation*

Geologic substrate and soil type greatly influence the type and distribution of plant communities in the Park. The dominant vegetative cover type is the pinyon (*Pinus edulis*)/ juniper *(Juniperus osteosperma*) community, covering about 40% of Arches National Park. Co-occurring species include blackbrush (*Coleogyne ramosissima*), squawbush (*Rhus* spp.), singleleaf ash (*Fraxinus anomala*), and serviceberry (*Amelanchier utahensis*). The blackbrush/shrubland community covers about 20% of the Park and is restricted to shallower soils and drier sites with blackbrush occurring in almost pure stands on the shallowest sites. Grassland plant communities cover about 11% of the Park, mostly on deeper sandy soils. This grass community includes Indian ricegrass (*Achnatherun hymenoides*), needle and thread grass (*Stipa comata*), galleta grass (*Pleuraphis jamesii*), and Mormon tea (*Ephedra* spp.). Saline soils cover about 2% of the Park, and these sites are dominated by the saltbush community, with saltbush (*Atriplex* spp.), snakeweed (*Gutierrezia* spp.), seepweed *(Suaeda* spp.), and greasewood (*Sarcobatus vermiculatus*). Riparian communities include such woody plants as cottonwood (*Populus fremontii*), willow (*Salix* spp.), big sagebrush (*Artemisia tridentata*), rabbitbrush (*Chrysothamnus* spp.), and greasewood. Hanging gardens are a unique plant community type at seeps and springs on rock canyon walls (described in detail by May et al. 1995, Fowler 1996, Fowler et al. 1996). Arches National Park supports a variety of lichens and micro-biotic soil crust communities which may be important contributors of ecosystem nitrogen and stabilizers of soil surfaces. Important exotics in the Park are Russian thistle (*Salsola tragus*), tamarisk (*Tamarix ramossisima*), and cheatgrass (*Bromus tectorum*). Complete species lists for the Park can be found in NPFlora, Harrison et al. (1964) and Sharpe (1993). NPLichen provides a listing of lichen species found in the park.

There are no known Threatened and Endangered Plant Species (Threatened and Endangered Species Information Institute 1993), but National Park Service species of concern include: canyonlands biscuit root (*Lomatium latilobum*), alcove death camas (*Zigadenus vaginatus*), and alcove bog-orchid (*Habenaria zothecina*).

## Air Quality

Monitoring of air quality at Arches included ozone and $SO_2$ concentrations from 1988-1992, NADP monitoring at Green River from 1985-present, and IMPROVE monitoring of visibility properties from 1988-1992. The IMPROVE particle monitor is near the campground at Skyline Arch, and the camera is near the turnoff for Cove and Turret Arches.

### *Emissions*

Table 3-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 10 counties surrounding Arches National Park. The largest sources of $SO_x$ in Emery and Carbon Counties in Utah are three Pacificorp plants (Huntington, Hunter, and Gate), and the largest source in Mesa County, Colorado is the Public Service Company's Cameo plant.

No estimates have been made for the influence of various regions on local air quality in Arches, but studies from nearby Canyonlands National Park probably characterize the Arches area well. Eatough et al. (1996) apportioned the $SO_x$ in Canyonlands to emission sources over a 3-month period from January through March in 1990, based on "fingerprints" of ratios of compounds in the air, and air mass trajectories. For example, emissions from 2 coal-fired power plants had high ratios of spherical aluminosilicate particles to sulfate, but very low ratios of arsenic to sulfate. Air from Arizona was characterized by low ratios of these aluminosilicate particles to sulfate, and high ratios of arsenic to sulfate. They concluded that $SO_x$ in Canyonlands derived from a wide range of regional sources rather than from a dominant source; about 37% (during a 21 day period) came from the southwest, 20% from the south/southeast, 19% from the north/northeast, and 23% from the northwest. Eatough et al. (1996) concluded that the major sources of $SO_2$ were from the southwest, while major sources of particulate sulfate were from the southeast. To the northwest at Green River, Eatough et al. (1996) found a larger portion of the $SO_x$ came from the southeast, and substantially less from the Utah Power and Light (now Pacificorp) generating stations to the North in the Green River Basin.

Table 3-1. Emissions (tons/day) for counties surrounding Arches National Park (Radian 1994).

| County | CO | $NH_3$ | NOx | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Carbon, UT | 43.3 | 0.5 | 17.1 | 17.5 | 131.9 | 16.8 |
| Emery, UT | 40.5 | 0.7 | 113.8 | 56.0 | 273.5 | 51.7 |
| Garfield, UT | 13.7 | 0.6 | 1.5 | 63.0 | 252.6 | 0.2 |
| Grand, UT | 17.0 | 0.2 | 1.6 | 47.4 | 184.7 | 0.2 |
| San Juan, UT | 40.8 | 0.7 | 3.9 | 102.7 | 405.4 | 0.5 |
| Uintah, UT | 55.2 | 1.5 | 6.2 | 44.5 | 286.2 | 0.8 |
| Wayne, UT | 6.3 | 0.6 | 0.7 | 30.3 | 122.4 | 0.1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mesa, CO | 118.4 | 2.9 | 25.6 | 32.8 | 196.7 | 9.0 |
| Montrose, CO | 49.7 | 2.3 | 6.6 | 22.0 | 95.2 | 1.9 |
| San Miguel, CO | 11.5 | 0.7 | 1.3 | 10.6 | 45.2 | 0.1 |

### *Air Pollutant Concentrations*

The concentrations of ozone in 1988 to 1992 averaged between 30 and 45 ppb, with peak 1-hr concentrations of 55 to 90 ppb (Table 3-2).

Table 3-2. Concentrations of ozone and $SO_2$ for Arches National Park between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the Sum60 exposure (ppb-hr in excess of 60 ppb for 12 hr/day for 3 months); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ measured 24-hr/day by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1988 | | |
| Mean | 44 | 0.2 |
| Sum60 | 7596 | |
| Max | 70 | 0.6 |
| 1989 | | |
| Mean | 45 | 0.2 |
| Sum60 | 6117 | |
| Max | 87 | 1.0 |
| 1990 | | |
| Mean | 28 | 0.2 |
| Sum60 | 0 | |
| Max | 56 | 1.2 |
| 1991 | | |
| Mean | 36 | 0.2 |
| Sum60 | -- | |
| Max | 74 | 0.6 |
| 1992 | | |
| Mean | 46 | 0.2 |
| Sum60 | -- | |
| Max | 76 | 0.5 |

## *Visibility*

Visual air quality was monitored at Arches from March 1988 through May 1992, using the aerosol sampler of the IMPROVE project. The data from this IMPROVE site have been summarized based on seasons of spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). Visual air quality was also monitored using a camera from July 1986 through November 1991.

## Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient ($b_{ext}$) from experimentally determined extinction efficiencies of certain species (Table 3-3). Table 3-3 provides a summary of the reconstructed extinction from the aerosol sampler data, presented as seasonal and annual 50th and 90th percentile standard visual range for Arches. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions.

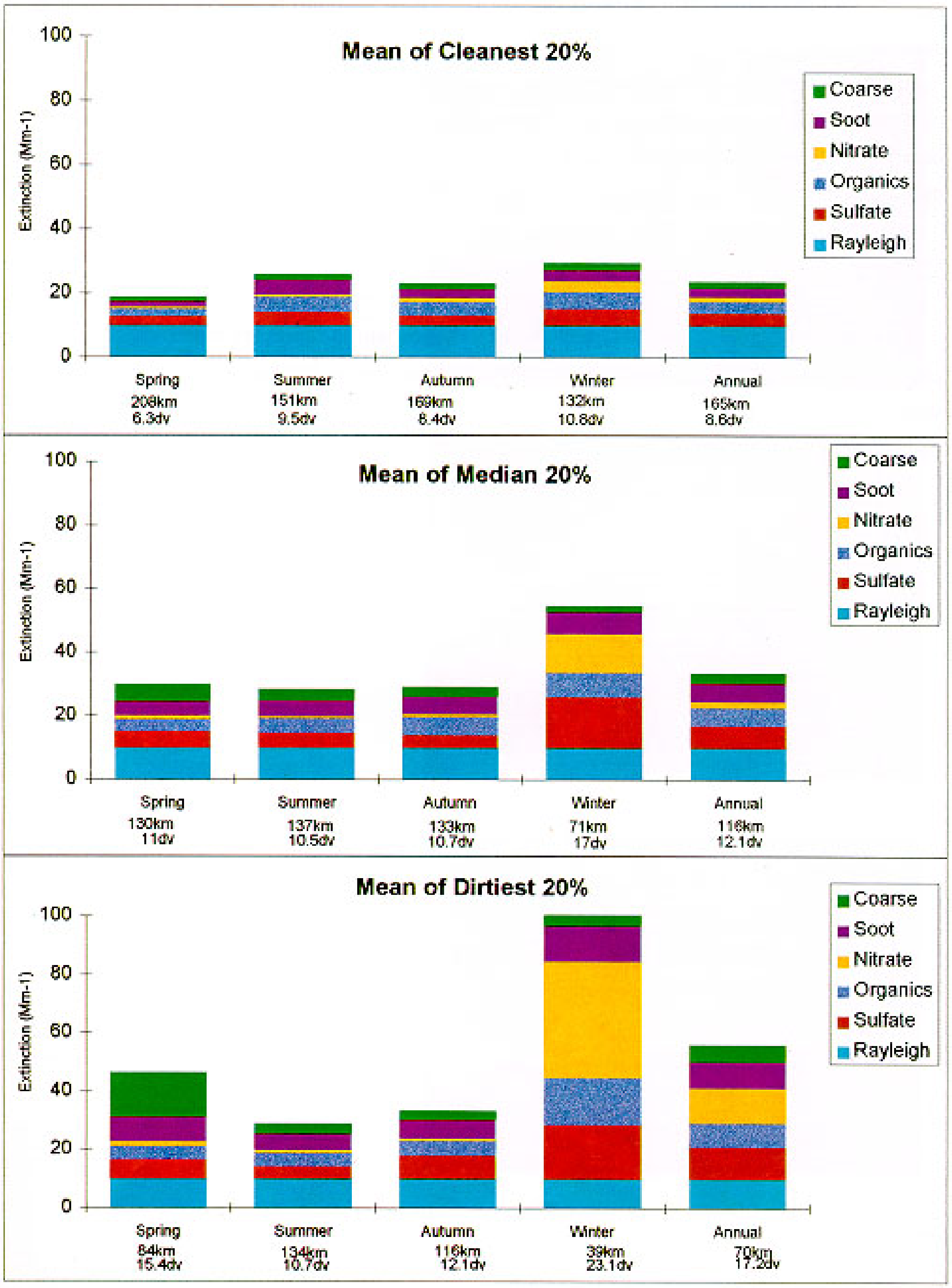
Table 3-3. Reconstructed visual range and light extinction coefficients for Arches National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentiles, March 1988 - May 1992.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 82 | 47.7 | 140 | 27.9 |
| Spring | 136 | 28.8 | 179 | 21.8 |
| Summer | 132 | 29.6 | 160 | 24.4 |
| Autumn | 131 | 29.8 | 173 | 22.6 |
| Annual | 120 | 32.6 | 163 | 23.9 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Arches to specific aerosol species (Figure 3-4). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of the days, mean of median 20% of the days, and mean of dirtiest 20% of the days. The "dirtiest" and "cleanest" signify highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution of all days. Each budget includes the corresponding extinction coefficient, standard visual range (SVR), and haziness in deciviews (dv). The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gasses. Higher fractions of extinction due to Rayleigh scattering indicates cleaner conditions.

Figure 3-4. Reconstructed extinction budgets for Arches National Park, March 1988 through May 1992.

**Figure 3-4. Reconstructed extinction budgets For Arches NP, March 1988 through May 1992.**



Atmospheric light extinction at Arches, like many rural western areas is largely due to sulfate, organic, and soot aerosols. The best visibility (excluding weather) occurs during the summer seasons.

In pre-industrial times, visibility would vary with patterns in weather, with winds (and the effects of winds on coarse particles), and with smoke from fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions, but the cleanest 20% of the days probably approach natural conditions (GCVTC 1996).

## Photographs

Three photos are provided from the Arches camera data to represent the range of visibility conditions at the park (Figure 3-5). The photos were chosen to provide an idea of the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what an observer sees.

Figure 3-5. Photographs representing visibility conditions at Arches National Park.

Figure 3-5. Photographs representing visibility conditions at Arches National Park.

**Arches National Park**
on a “clear” day.

Representative Conditions:
Visual Range: 340 - 391 km
$b_{ext}$: 12 - 10 $Mm^{-1}$
Haziness: 1 - 0 dv

**Arches National Park**
on a “average” day.

Representative Conditions:
Visual Range: 210 - 250 km
$b_{ext}$: 19 - 16 $Mm^{-1}$
Haziness: 6 - 4 dv

**Arches National Park**
on a “dirty” day.

Representative Conditions:
Visual Range: 110 - 140 km
$b_{ext}$: 36 - 28 $Mm^{-1}$
Haziness: 13 - 10 dv

### *Atmospheric Deposition*

The rates of atmospheric deposition for Green River, Utah (about 70 km northwest of Arches) are relatively low (Table 3-4). Precipitation pH averages about 5.2. Deposition of N averages about 1 kg N $ha^{-1}$ $yr^{-1}$, which is slightly higher than the rate of S deposition. The deposition of both ammonium and nitrate showed significant increasing trends from 1985 through 1994. Ammonium-N deposition increased by about 0.04 kg N $ha^{-1}$ $yr^{-1}$ ($r^2$=0.53, p<0.02) while nitrate-N deposition increased at a rate of 0.03 kg N $ha^{-1}$ $yr^{-1}$ ($r^2$ = 0.44, p<0.04). However, the significance of these trends depends completely on the very low values for the first year of monitoring (1985) when data completeness averaged only 54%. Even if these values were doubled, we suspect the data would be unreliable, being far lower than any other year. We conclude that N deposition probably has not been increasing at Green River. Sulfate deposition showed no trend during this period. There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 3-4. Atmospheric deposition for Green River, Utah (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentration (mg/L) | | | Deposition (kg $ha^{-1}$ $yr^{-1}$) | | | | Conductivity | Precipitation |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | (μS/mm) | (mm/yr) |
| 1985 | 0.01 | 0.30 | 0.49 | 0.01 | 0.22 | 0.37 | 5.55 | 0.64 | 75 |
| 1986 | 0.17 | 1.19 | 1.36 | 0.31 | 2.10 | 2.40 | 5.78 | 1.57 | 177 |
| 1987 | 0.48 | 1.27 | 1.40 | 0.86 | 2.26 | 2.49 | 5.35 | 1.18 | 178 |
| 1988 | 0.48 | 1.75 | 1.47 | 0.63 | 2.30 | 1.94 | 5.22 | 1.42 | 132 |
| 1989 | 0.94 | 2.13 | 1.94 | 0.59 | 1.35 | 1.23 | 6.83 | 2.68 | 63 |
| 1990 | 1.00 | 2.04 | 2.17 | 0.66 | 1.35 | 1.43 | 5.82 | 2.40 | 66 |
| 1991 | 0.43 | 1.42 | 1.22 | 0.83 | 2.72 | 2.34 | 5.74 | 1.32 | 192 |
| 1992 | 0.90 | 1.50 | 1.54 | 1.50 | 2.51 | 2.58 | 5.90 | 1.54 | 167 |
| 1993 | 0.53 | 1.33 | 1.33 | 1.10 | 2.77 | 2.77 | 5.58 | 1.14 | 208 |
| 1994 | 0.40 | 1.35 | 1.05 | 0.61 | 2.06 | 1.60 | 5.44 | 1.45 | 150 |

## Sensitivity of Plants

No visible injury signs of any air pollution damage have been reported for vegetation in or near Arches. Almost none of the Park's species have been tested under controlled conditions for sensitivity to pollutants. Based on the ozone concentrations required to affect very sensitive plants in controlled environments, it is possible that current ozone exposures could be high enough to affect some species. However, in the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

The Colorado River forms 17.5 km of Arches National Park's eastern and southern boundaries, from the mouth of Salt Wash. The ephemeral streams in the park drain into the Colorado River. Because of high sediment loads the conductivity and acid-neutralizing capacity of this river is very high, providing extreme resistance to acidification. However, the Park also has small pothole aquatic systems that are of interest relative to their potential sensitivity to acidification.

Graham (1991) and Gladney et al. (1993) studied the ecology and chemistry of rock pools in Arches during 1988; the potholes ranged in volume from 1700 L to 8200 L. The pH of pothole waters ranged from 6.5-9.5, with a total alkalinity ranging from 17-47 mg/L (340-940 μeq/L). The measured nitrate-N varied in the rock pools from less than 0.2 to 1.5 mg/L.

During rock pool acidification experiments (lowering the pH to 5.5, 5.0 and 4.5), sediments and suspended particles in the rock pools tended to buffer the introduced acidity rapidly (within 24 hours) (Graham 1991). These sediment-water interactions lessen the sensitivity of rock pools to acidification. Many of the experimental systems were located on sandstone bedrock. It was suggested that rock pools situated on bedrock more resistant to weathering could be more susceptible to acid inputs.

Dodson (1991) speculated that atmospheric deposition of nitrogen compounds to rock pools may result in nutrient enrichment leading to algal blooms and oxygen depletion. However, no data are available to test this idea, or to gauge the magnitude of N and C inputs from deposition vs. allochthonous litter sources.

### *Aquatic Invertebrates*

Dodson (1987) and Graham (1991) report on the types of organisms found in rock pools in Arches National Park. Three types of biological communities can be found in these rock pools:

- gnats, mosquitoes, and frog tadpoles occur in the most ephermeral pools,
- fairy shrimp occur in slightly longer-lived pools,
- insects, cladocerans, copepods, and salamander larvae occur in permanent pools.

Experiments with acidification of rock pools found near Arches caused mortality to larval crustacea (pH reduced from 7.0 to 4.5); dipteran larvae and ostracods did not appear to be affected at pHs as low as 4.5.

### *Amphibians*

Graham (1991) stated that potholes on the Colorado Plateau are used by the red-spotted toad (*Bufo punctatus)* and the Great Basin spadefoot toad (*Scaphiopus intermontanus)* for egg laying and larval development. Pierce (1991) conducted a series of acidification experiments in potholes to determine the response of these amphibian larvae to acidity. *Bufo punctatus* larvae were relatively insensitive to lowered pHs, with 100% survival at all treatments except pH 3.5. However, *Scaphiopus intermontanus* larvae hatching success was significantly reduced at pH 5.0. These experimental results need to be interpreted with caution because of the short duration of the experiments and the limited number of individuals tested *in situ*.

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and these apply to Arches National Park. The two most important recommendations relative to Arches are:

- Reinstitute monitoring of air quality. Air quality monitoring stopped in 1992 at Arches, even though Arches National Park remains a federally designated Class I area. Levels of pollution monitored at Canyonlands National Park may approximate the levels that occur in Arches, but the special legislative status of Class I designation warrants on-site monitoring at Arches. The IMPROVE network is designed to provide regional information on air pollution, and sampling at Canyonlands and Bryce Canyon is sufficient to meet IMPROVE's goals. However, any influence of local pollution sources or air masses that do not reach the IMPROVE sites would not be monitored at present. Therefore, smaller-scale monitoring of visibility would provide some valuable on-site data for determining conditions at Arches.

- Two levels of vegetation surveys for visible injury on plant leaves should be conducted. The first level would be a reconnaissance by an expert in pollution injury symptoms in late summer. If signs of injury are apparent, then a detailed survey program could be developed. If no signs of injury are found, then the survey could be repeated following any summer with unusually high ozone concentrations. Unfortunately, the state-of-knowledge is too poorly developed for us to identify which species at Arches might be most sensitive to ozone, but we expect that cottonwood (*Populus fremontii*), single-leaf ash (*Fraxinus anomala*), and squawbush (*Rhus trilobata*) might be among the more sensitive species.
- None of the pothole systems monitored in the Park had ANCs less than 200 ueq/l, so acidification is unlikely for pools located on sandstone substrates. We recommend that the geology of Arches be reviewed to determine if rock pools exist on bedrock more resistant to weathering. If such systems are identified by map inspection and field surveys, we recommend that grab samples for water chemistry analysis be collected and analyzed for pH, ANC, conductance, and major anions and cations.

## Park Summary

Visibility is currently the only AQRV known to be impacted by pollution, as with the other NPS Class I areas of the Colorado Plateau. Current levels of pollution in southern Utah are high enough to produce haze and obscure the important vistas of Arches and surrounding areas. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Arches National Park.

Little information has been collected on air pollution effects on the Park’s biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants. A reconnaissance survey should be done in late summer to look closely for any signs of foliar injury that might result from ozone exposure.

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# Chapter 4. Bandelier National Monument

## Introduction

Bandelier was declared an archeological monument by the U.S. Department of Agriculture (USDA) in 1916 as part of the Santa Fe National Forest. The Monument was named in honor of Adolf Bandelier, an archeologist of the late 1800's who worked extensively in the region. The Presidential proclamation stated:

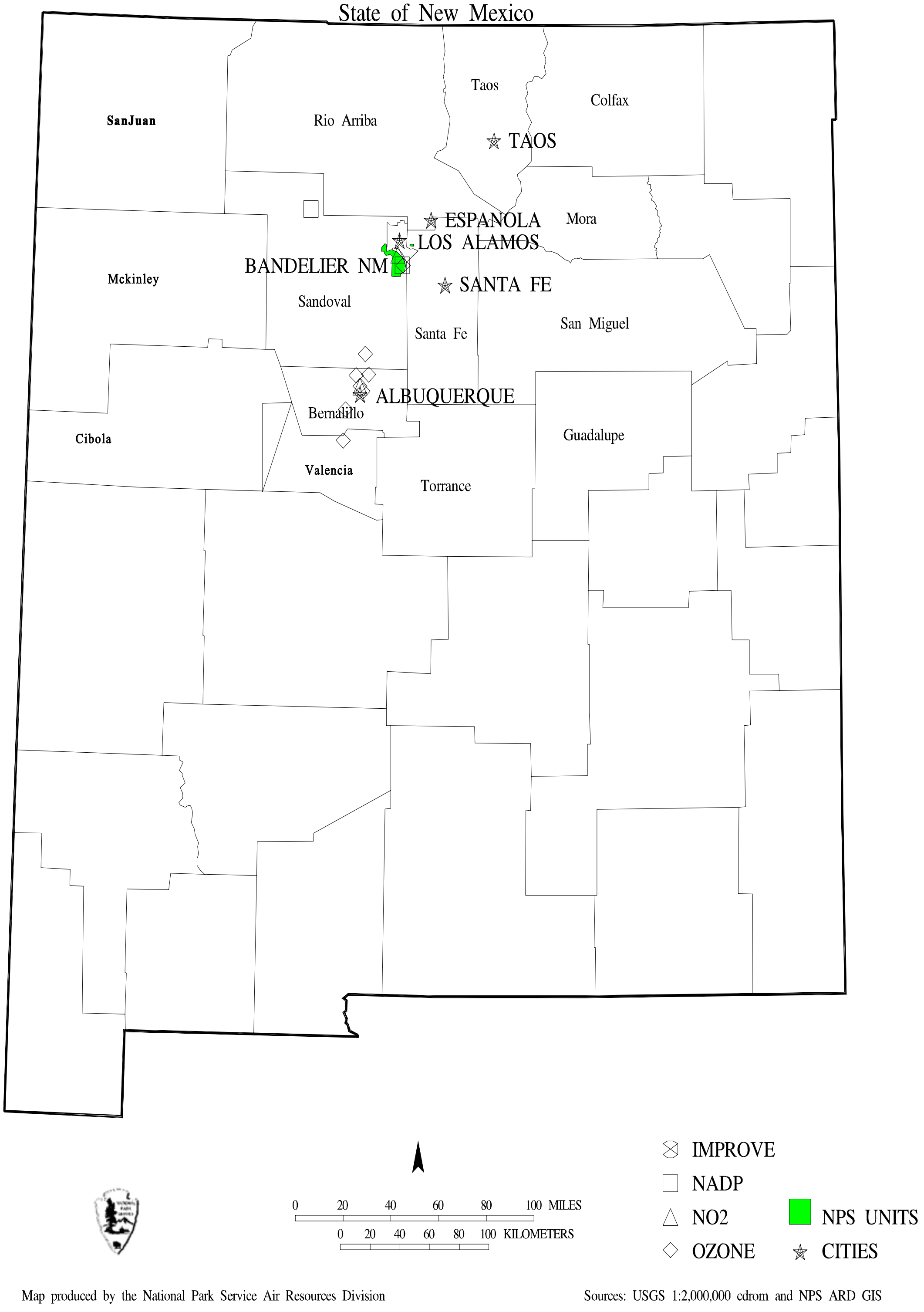
> " Certain prehistoric aboriginal ruins.., are of unusual ethnologic, scientific, and educational interest, and it appears that the public interests would be promoted by reserving these relics of vanished people, with as much land as may be possible for the proper protection there of..."

In 1932 the Monument was reassigned from the Forest Service to the NPS in the Department of Interior. Bandelier National Monument covers approximately 13,250 ha of federally owned land (Figure 4-1). In 1972, the unique and valuable natural resources of Bandelier were officially recognized and the Bandelier Wilderness was created, comprising 9,425 ha of the Monument. The elevation of Bandelier ranges from 1,590 m at the Rio Grande to 3,190 m at the summit of Cerro Grande. Bandelier is located on the southern portion of the Pajarito Plateau on the eastern flank of the Jemez Mountains, a range forming the southern edge of the Rocky Mountains. The Monument has portions in Sandoval, Los Alamos and Santa Fe counties, and is adjacent to Los Alamos National Laboratory. The Anasazi occupied the region of the Park between about 1100 and 1600 A.D. and their culture left an incredible density of sites (an average of 1 site/2.7 ha).

### *Geology and Soils*

The region surrounding Bandelier has been shaped by faulting that started as early as 30 million years ago. This late Cenozoic Era faulting resulted in the Rio Grande Rift, and widespread intrusions and volcanism from late in the Tertiary Period into the Pleistocene. About 1 million years ago, an intense volcanic event formed what is now the Jemez Caldera and released tremendous volumes of ash and pumice while fragmenting and displacing huge amounts of basaltic rock. The ash flows became the Bandelier Tuff that forms most of the walls of Frijoles and surrounding canyons. The differential cooling and cementing of this 30 m thick layer of tuff resulted in material

Figure 4-1. Location of Bandelier National Monument.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

that spatially varies in its resistance to weathering; the slower-cooling middle is more resistant to erosion than either the top or bottom of the layer. This variability has resulted in the alternating mesa and canyon topography of the region and of the Monument. The relatively soft and poorly consolidated material allowed prehistoric people to carve homes and granaries out of small caves and alcoves that formed naturally along the side walls of the region's canyon (Chronic 1986).

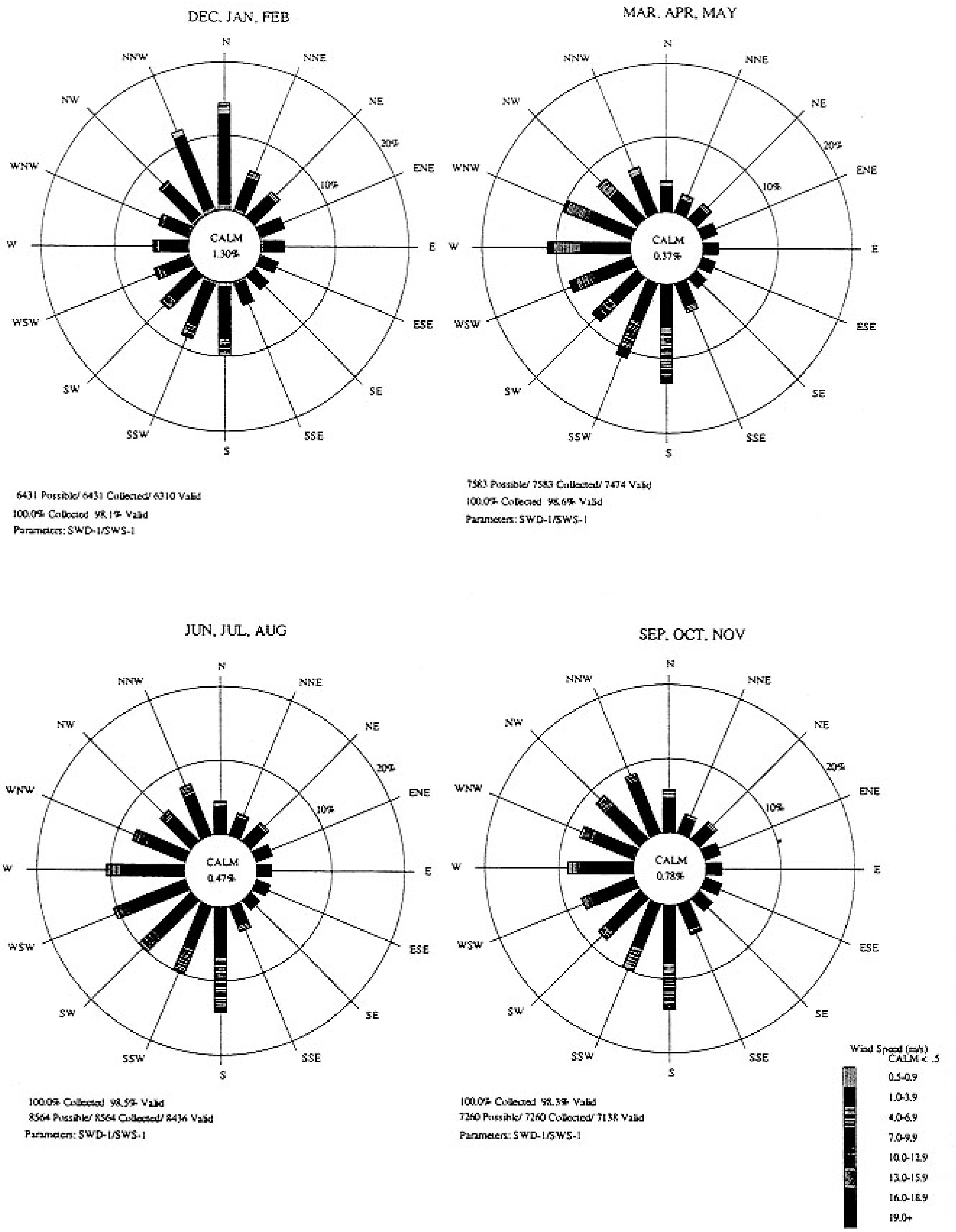
Soils in Bandelier are variable and range from soils derived mostly from rhyolitic tuff or pumice to cobbly colluvial and alluvial soil material at the foot of canyon walls. Over most of the southern portion of the Monument, soils are derived from the volcanic rhyolitic tuff and are thin and easily eroded. This erosion is currently a major concern for the Monument, especially in the pinyon/juniper zone which occurs throughout much of the park. Erosion is believed to have been accelerated by over-grazing in historic times by cattle and feral burros. Most soils are somewhat fertile, with relatively high concentrations of available base cation nutrients. Some mesa-top soils are more stable, moderately deep to deep, and are more weathered with higher organic content than soils found in other parts of the Monument.

### *Climate*

Bandelier has a semi-arid to sub-humid climate, receiving an average of 410 mm/yr of precipitation (ranging from 340 mm/yr at lower elevation to 650 mm/yr at higher elevations). Lower elevation sites receive rain in July and August, and higher elevation sites also receive winter precipitation. The mean annual temperature is $10^{o}$ C with higher elevation sites being cooler. At the visitor center, the winds in winter come primarily from the north and from the west, shifting more westward and southward in the other seasons (Figure 4-2). In the western end of Bandelier, stronger winds are predominantly from the northwest reflecting a dominant drainage flow out of the Jemez mountains while variation in lighter winds is considerable. The eastern end of Bandelier receives winds primarily from the south because of air channeling through the Rio Grande Depression. This southerly flow from Albuquerque is particularly important for air quality.

Figure 4-2. Seasonal wind roses for Bandelier National Monument (1990-1993).

Figure 4-2. Seasonal wind roses for Bandelier National Monument (1990-1993).



### *Vegetation*

The dry climate at Bandelier strongly controls the species composition of communities and the relative abundances of species. Most of the vegetation cover in Bandelier has been mapped, and several studies have examined the impacts of disturbance on plant communities. Bandelier National Monument is characterized by several dominant plant community types. Pinyon *(Pinus edulis*)/juniper(*Juniperus monosperma, J. scopulorum*), covering about 5,300 ha, and ponderosa pine *(Pinus ponderosa*)/mixed conifer are the dominant vegetation types in the Monument followed by grasslands, meadows and mountain mahogany (*Cercocarpus montanus*)/Apache plume *(Fallugia paradoxa*) shrublands. At higher elevations on north slopes, mixed conifer grades to Douglas-fir (*Pseudotsuga menziesii*)/white fir (*Abies concolor*)/ aspen (*Populus tremuloides*) and Douglas-fir/Engelmann spruce (*Picea engelmannii)*. Species commonly found in grassland communities and in the understory of the woody plant communities include: blue grama *(Bouteloua gracilis*), black grama (*Bouteloua eriopoda*), bluestem (*Andropogon* spp.), and galleta grass (*Pleuraphis jamesii*). Bluegrass (*Poa* spp.), Junegrass (*Koeleria nitida*), mountain brome (*Bromus* sp.), mountain muhly (*Muhlenbergia montana*) and Arizona fescue (*Festuca arizonica*) occur on mesas and at higher elevations. The lichens and microphytic soil crusts of Bandelier are recognized as important components of native ecosystems and have been objects of research interest (Loftin and White *in press*, Chong 1992, Weber 1980). Complete lists of Monument flora are found in NPFlora and are also provided by Potter and Foxx (1979). Lichen lists can be found in NPLichen, Jones (1979) and Wetmore (1983). There are no known Threatened and Endangered Plant Species (Threatened and Endangered Species Information Institute 1993), or NPS species of special concern. One animal species of special concern to the NPS occurs in the Monument: *Plethodon neomexicanus*, the Jemez Mountain salamander.

## Air Quality

Air quality monitoring for Bandelier consists of data from 1990-1994 for ozone concentration, NADP monitoring from 1982 to the present, sulfur dioxide measurements from 1988-1994, and IMPROVE monitoring for visibility from 1988 to the present.

### *Emissions*

Table 4-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 15 counties surrounding Bandelier National Monument. No information is available to relate these emissions to air quality at Bandelier, or to apportion Bandelier's air quality impairment to local and regional sources. The largest local producers of $SO_X$ in San Juan County include two power plants (Arizona Public Service's 4 Corners plant, and Public Service Company's San Juan Generating plant) and Western Gas Processors' San Juan facility.

Table 4-1. 1994 Emissions (tons/day) for counties surrounding Bandelier National Monument (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Bernalillo, NM | 581.1 | 1.45 | 98.21 | 9.06 | 229.65 | 13.87 |
| Cibola, NM | 6.24 | 0.07 | 4.44 |  | 199.37 | 2.32 |
| Colfax, NM | 24.95 | 1.14 | 4.14 | 38.21 | 34.07 | 1.54 |
| Guadalupe, NM | 15.06 | 1.04 | 2.09 | 23.8 | 27.35 | 0.22 |
| Los Alamos, NM | 14.35 | 0.04 | 1.58 | 1.25 | 5.36 | 0.16 |
| McKinley, NM | 151.19 | 2.22 | 40.84 | 47.42 | 319.85 | 7.99 |
| Mora, NM | 16.87 | 0.66 | 1.89 | 18.62 | 24.89 | 0.21 |
| Rio Arriba, NM | 91.03 | 1.32 | 15.92 | 71.56 | 263.55 | 1.29 |
| Sandoval, NM | 91.72 | 0.22 | 13.37 | 36.34 | 176.17 | 1.42 |
| San Juan, NM | 166.63 | 1.17 | 196.56 | 50.16 | 371.94 | 175.53 |
| San Miguel, NM | 44.77 | 1.32 | 6.04 | 46.82 | 53.13 | 0.88 |
| Santa Fe, NM | 144.44 | 0.44 | 19.84 | 16.90 | 141.74 | 2.19 |
| Taos, NM | 64.17 | 0.43 | 8.25 | 23.87 | 92.19 | 0.96 |
| Torrance, NM | 26.13 | 1.32 | 5.61 | 27.59 | 44.10 | 0.37 |
| Valencia, NM | 127.07 | 0.77 | 16.77 | 56.02 | 213.12 | 1.84 |

### *Air Pollutant Concentrations*

The concentrations of ozone between 1990 and 1994 averaged about 50 ppb, with peak 1-hr concentrations of 75 to 90 ppb (Table 4-2). These concentrations fall within a range that may produce visible injury or growth effects on very sensitive species (see Chapter 2), but no effects have been noted. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Table 4-2. Concentrations of ozone and $SO_2$ for Bandelier National Monument between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the Sum60 exposure (ppb-hr in excess of 60 ppb for 12 hr/day for 3 months); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ measured 24-hr/day by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1988 | -- | |
| Mean | | 0.1 |
| Sum60 | | |
| Max | | 1.9 |
| 1989 | -- | |
| Mean | | 0.1 |
| Sum60 | | |
| Max | | 0.5 |
| 1990 | | |
| Mean | 48 | 0.1 |
| Sum60 | 15199 | |
| Max | 81 | 0.5 |
| 1991 | | |
| Mean | 48 | 0.0 |
| Sum60 | 28265 | |
| Max | 87 | 0.6 |
| 1992 | | |
| Mean | 46 | 0.1 |
| Sum60 | 13070 | |
| Max | 78 | 0.3 |
| 1993 | | |
| Mean | 44 | |
| Sum60 | 8490 | |
| Max | 77 | |
| 1994 | | |
| Mean | 46 | |
| Sum60 | 19155 | |
| Max | 90 | |

### *Visibility*

Bandelier National Monument is about 64 km west of Santa Fe, and 80 km northwest of Albuquerque. Visual air quality has been monitored since 1988, using a transmissometer, an aerosol sampler and a camera at locations near the fire lookout on Frijoles Mesa. The camera operated from July 1978 to April 1995. Bandelier National Monument is part of the IMPROVE Monitoring Network. The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period May 1988 through February 1994, based on seasons of spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

#### Optical Data - Transmissometer

The transmissometer system consists of two individually-housed primary components: a transmitter (light source) and a receiver (detector). The atmospheric extinction coefficient ($b_{ext}$) at any time can be calculated based on the intensity of light emitted from the source and that measured by the receiver (along with the path length between the two). Transmissometers provide continuous, hourly $b_{ext}$ measurements. Weather factors such as clouds and rain can affect transmissometer measurements, but these can be "filtered out" by removing data points with high relative humidities (RH>90%).

The data are presented by season and annual median values, with and without meteorological factors, in Table 4-3. The data are presented in units of extinction coefficient in $Mm^{-1}$ and standard visual range in km. Extinction coefficients represent the ability of the atmosphere to scatter and absorb light. Median values with large differences between the extinction values "including weather" and "excluding weather" indicate periods dominated by precipitation. Higher extinction coefficients signify lower visibility. Similarly, season and annual medians with nearly equal "including weather" and "excluding weather" extinctions indicate visibility reduction caused principally by particles.

Table 4-3. Transmissometer data summary for Bandelier National Monument for 1988-1994. SVR = standard visual range; $b_{ext}$ = light extinction coefficient.

| Season Year | Excluding Weather | | Including Weather | |
|---|---|---|---|---|
| | Median of All Data | | Median of all Data | |
| | SVR (km) | $b_{ext}$ ($Mm^{-1}$) | SVR (km) | $b_{ext}$ ($Mm^{-1}$) |
| Autumn 1988 | 142 | 27 | 137 | 28 |
| Winter 1989 | 153 | 25 | 142 | 27 |
| Spring 1989 | 110 | 35 | 104 | 37 |
| Summer 1989 | 107 | 36 | 99 | 39 |
| Autumn 1989 | 124 | 31 | 120 | 32 |
| Annual 1989 | 120 | 32 | 113 | 34 |
| Winter 1990 | 120 | 34 | 113 | 34 |
| Spring 1990 | 117 | 33 | 110 | 35 |
| Summer 1990 | 107 | 36 | 107 | 36 |
| Autumn 1990 | 153 | 25 | 148 | 26 |
| Annual 1990 | 120 | 32 | 113 | 34 |
| Winter 1991 | 148 | 26 | 142 | 27 |
| Spring 1991 | 124 | 31 | 124 | 31 |
| Summer 1991 | 113 | 43 | 110 | 35 |
| Autumn 1991 | 107 | 36 | 99 | 39 |
| Annual 1991 | 120 | 32 | 113 | 34 |
| Winter 1992 | 124 | 31 | 113 | 34 |
| Spring 1992 | 117 | 33 | 110 | 35 |
| Summer 1992 | 104 | 37 | 102 | 38 |
| Autumn 1992 | 110 | 35 | 107 | 36 |
| Annual 1992 | 110 | 35 | 107 | 36 |
| Winter 1993 | 113 | 34 | 94 | 41 |
| Spring 1993 | 124 | 31 | 120 | 32 |
| Summer 1993 | 133 | 29 | 128 | 30 |

| | | | | |
|---|---|---|---|---|
| Autumn 1993 | 102 | 38 | 99 | 39 |
| Annual 1993 | 117 | 33 | 110 | 35 |
| Winter 1994 | 107 | 36 | 104 | 37 |
| Spring 1994 | 102 | 38 | 99 | 39 |
| Summer 1994 | 117 | 33 | 117 | 33 |
| Autumn 1994 | 137 | 28 | 133 | 29 |
| Annual 1994 | 117 | 33 | 113 | 34 |

No trends were apparent between 1988 and 1994. Visibility tends to be lower in spring and summer than in winter, including or excluding high humidity days (Table 4-4).

Table 4-4. Standard visual range for Bandelier National Monument. Seasonal averages for median standard visual range in km from October 1988 - November 1994.

| Season | Excluding Weather | Including Weather |
|---|---|---|
| Winter | 127 | 118 |
| Spring | 116 | 111 |
| Summer | 114 | 110 |
| Autumn | 125 | 120 |

Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 4-5). To compare this table with the data from Table 4-3 and 4-4, the "excluding weather" values should be used. The estimated visual ranges and light extinction coefficients are similar for both the transmissometer measurements and the reconstructed values based on aerosol concentrations. In Table 4-6 the data are presented as seasonal and annual 50th and 90th percentile standard visual range for Bandelier National Monument. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions. The measured extinction data are used to verify the calculated reconstructed extinction and can also be used to run plume and regional haze models and to analyze visibility trends and conditions. Because of the larger spatial and temporal range of the aerosol data, reconstructed extinction data are preferred.

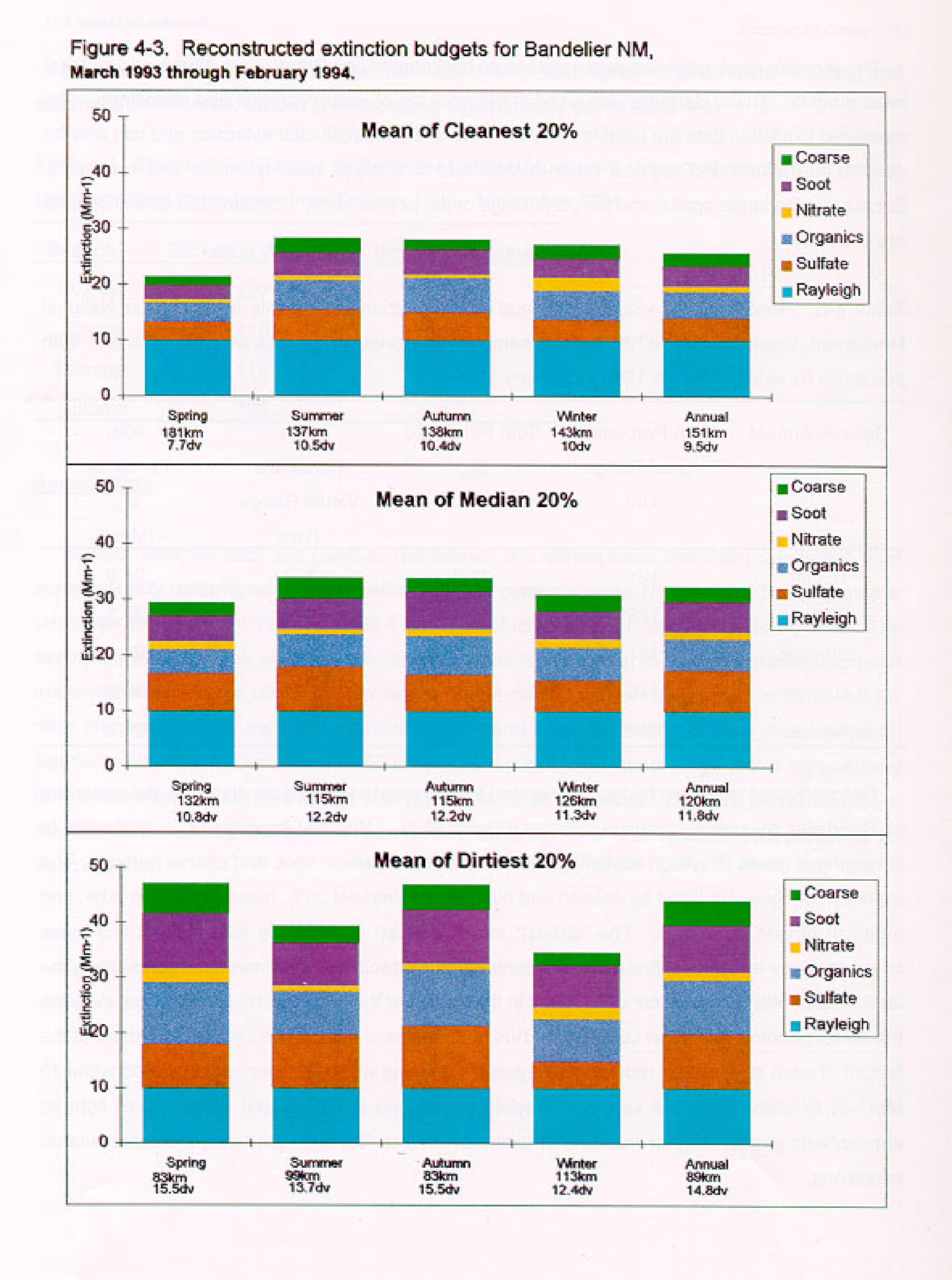
Table 4-5. Reconstructed visual range and light extinction coefficients for Bandelier National Monument, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentile by season, March 1988 - February 1994.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 121 | 32.3 | 157 | 24.9 |
| Spring | 125 | 31.4 | 177 | 22.1 |
| Summer | 121 | 32.3 | 149 | 26.2 |
| Autumn | 115 | 33.9 | 152 | 25.7 |
| Annual | 117 | 33.5 | 158 | 24.8 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Bandelier to specific aerosol species (Figure 4-3). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20%, mean of median 20%, and mean of dirtiest 20% days. The "dirtiest" and "cleanest" signify days with highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the

20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicates cleaner conditions.

Figure 4-3. Reconstructed extinction budgets for Bandelier National Monument, March 1993 through February 1994.



Atmospheric light extinction at Bandelier, like many rural western areas, results primarily from aerosols of sulfate, organic compounds, and soot. In pre-industrial times, visibility would vary with patterns in weather, winds (and the effects of winds on coarse particles), and fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions.

## Photographs

Three photos are provided to represent the range of visibility conditions at Bandelier (Figure 4-4). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what people see.

Figure 4-4. Photographs representing visibility conditions at Bandelier National Monument.

**Bandelier National Monument**
on a "clear" day.

Representative Conditions:
Visual Range: 350 - 391 km
$b_{ext}$: 11 - 10 $\text{Mm}^{-1}$
Haziness: 1 - 0 dv

**Bandelier National Monument**
on a "average" day.

Representative Conditions:
Visual Range: 200 - 240 km
$b_{ext}$: 20 - 16 $\text{Mm}^{-1}$
Haziness: 7 - 5 dv

**Bandelier National Monument**
on a "dirty" day.

Representative Conditions:
Visual Range: 100 - 120 km
$b_{ext}$: 39 - 33 $\text{Mm}^{-1}$
Haziness: 14 - 12 dv

### *Atmospheric Deposition*

The rates of atmospheric deposition for Bandelier are low (Table 4-6). Precipitation pH averages about 5.0. Deposition of N averages about 1.5 kg N ha$^{-1}$ yr$^{-1}$, which is similar to the rate of S deposition. No trend is apparent for the concentration or deposition of N, but S concentrations and deposition have declined since the late 1980s (see also Lynch et al. 1996). There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 4-6. Atmospheric deposition for Bandelier National Monument (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentrations (mg/L) | | | Deposition (kg ha$^{-1}$ yr$^{-1}$) | | | | Conductivity (µS/mm) | Precipitation (mm/yr) |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | | |
| 1982 | 0.18 | 0.61 | 1.03 | 0.64 | 2.17 | 3.66 | 5.15 | 0.79 | 356 |
| 1983 | 0.16 | 0.86 | 1.01 | 0.59 | 3.18 | 3.74 | 5.06 | 0.89 | 370 |
| 1984 | 0.17 | 0.90 | 1.03 | 0.63 | 3.36 | 3.84 | 5.03 | 0.90 | 373 |
| 1985 | 0.12 | 0.71 | 0.90 | 0.67 | 3.94 | 5.00 | 5.04 | 0.79 | 556 |
| 1986 | 0.11 | 0.71 | 0.90 | 0.62 | 4.02 | 5.09 | 5.01 | 0.80 | 566 |
| 1987 | 0.16 | 1.07 | 1.00 | 0.61 | 4.09 | 3.82 | 4.91 | 1.00 | 382 |
| 1988 | 0.05 | 0.78 | 0.89 | 0.26 | 4.10 | 4.68 | 4.89 | 0.91 | 526 |
| 1989 | 0.20 | 1.07 | 0.91 | 0.77 | 4.11 | 3.49 | 4.92 | 0.98 | 384 |
| 1990 | 0.19 | 0.77 | 0.80 | 0.75 | 3.05 | 3.17 | 5.06 | 0.80 | 396 |
| 1991 | 0.14 | 0.75 | 0.67 | 0.77 | 4.15 | 3.70 | 5.05 | 0.72 | 553 |
| 1992 | 0.16 | 0.76 | 0.74 | 0.57 | 2.69 | 2.62 | 5.07 | 0.74 | 354 |
| 1993 | 0.15 | 0.76 | 0.70 | 0.70 | 3.56 | 3.28 | 5.00 | 0.78 | 469 |
| 1994 | 0.15 | 0.86 | 0.66 | 0.67 | 3.83 | 2.94 | 4.96 | 0.81 | 445 |

## Sensitivity of Plants

No signs of injury from air pollution have been reported for vegetation in or near Bandelier National Monument. Only a few of the Monument's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Monument. Based on the ozone concentrations required to affect very sensitive plants (such as aspen), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers (with the possible exception of ponderosa pine), and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

Bandelier National Monument is located on a plateau which is cut by three stream drainages: Frijoles, Alamo, and Capulin Canyons. Frijoles Canyon contains a permanent stream, El Rio de los Frijoles; Capulin Creek flows year round only in the upper third of the canyon, and Alamo Creek carries permanent water only in the northern part of its canyon. A portion of the Rio Grande runs through the Monument on its eastern border. Some water quality monitoring of streams and rivers in the Monument has been carried out as part of the National Water Quality Assessment of the U.S. Geological Survey.

Water quality data were collected in Bandelier June 1977-September 1978 (following the Mesa fire) by Purtymun and Adams (1980). The range of pH reported for the Rio Grande was 8.3-8.5. The stream reaches within the monument had pH values of 7.3-8.5. The bicarbonate buffering and ANC were very high for both the river and the streams: bicarbonate buffering capacity of 139-156 mg/l (2780-3120 μeq/L ANC) for the Rio Grande and 40-85 mg/L (800-3700 μeq/L) bicarbonate for the stream reaches. A map of sample locations within the Monument is included in Figure 4-5, and Table 4-7 provides representative water quality data for major creek drainages collected by Purtyman and Adams (1980). The buffering in the Rio Grande and surface streams of the Monument is sufficient to prevent any change in pH due to acidic deposition.

Figure 4-5. Streams of Bandelier National Monument (area burned in La Mesa fire is shaded).

Figure 4-5. Streams of Bandelier National Monument (area burned in La Mesa fire is shaded).

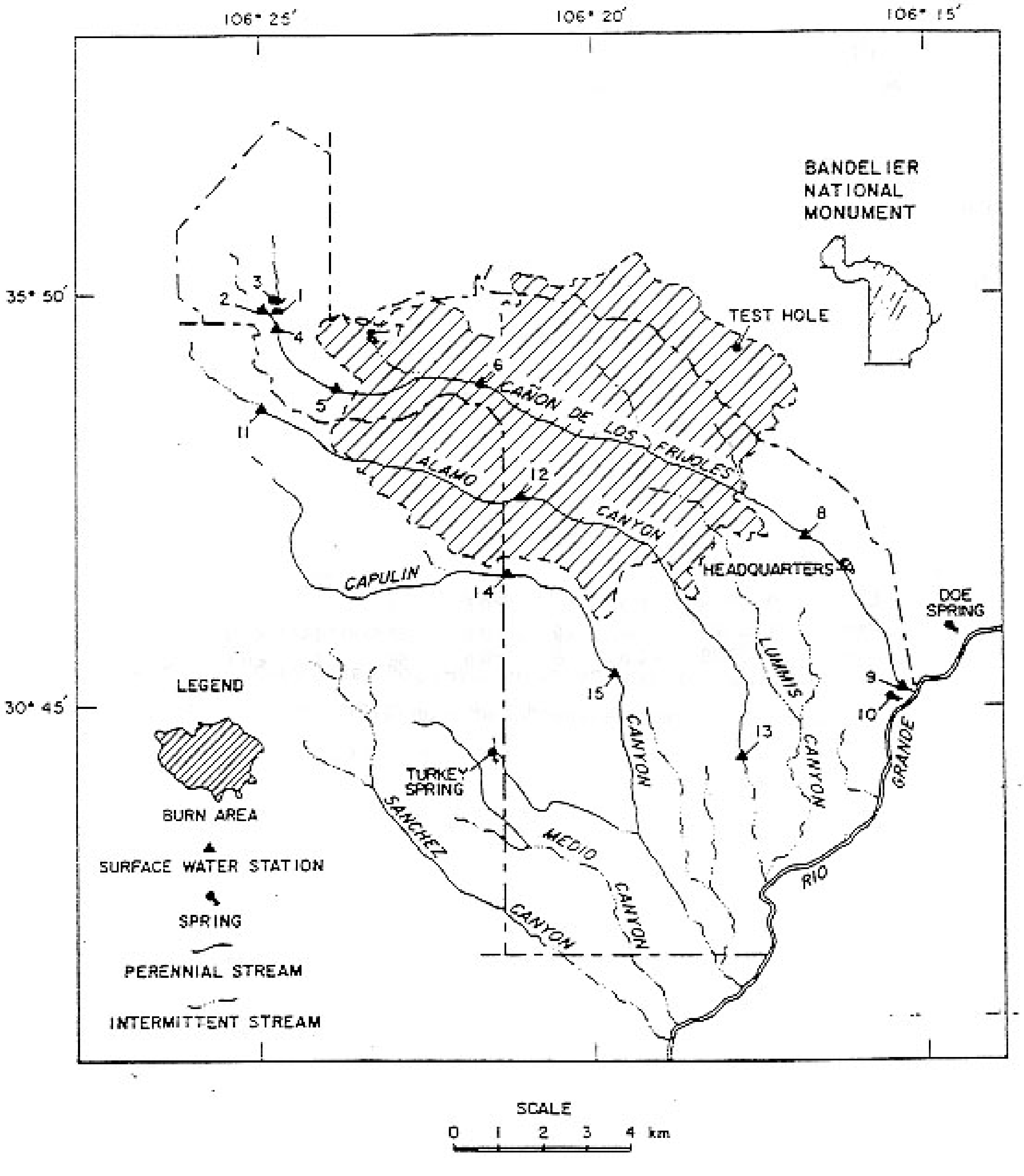


Table 4-7. Water chemistry for streams in Bandelier National Monument in the late 1970s (from Purtyman and Adams 1980).

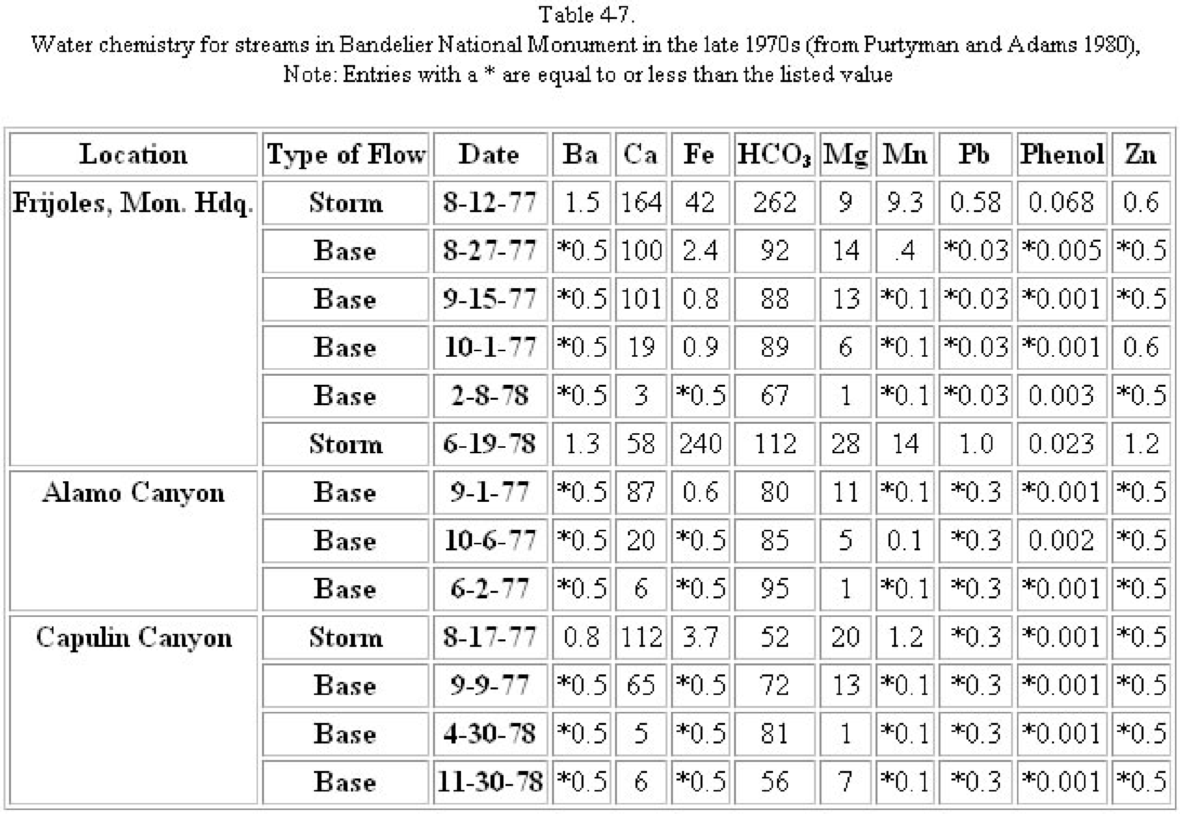


Table 4-7.
Water chemistry for streams in Bandelier National Monument in the late 1970s (from Purtyman and Adams 1980),
Note: Entries with a * are equal to or less than the listed value

| Location | Type of Flow | Date | Ba | Ca | Fe | $HCO_3$ | Mg | Mn | Pb | Phenol | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Frijoles, Mon. Hdq.** | **Storm** | **8-12-77** | 1.5 | 164 | 42 | 262 | 9 | 9.3 | 0.58 | 0.068 | 0.6 |
| | **Base** | **8-27-77** | *0.5 | 100 | 2.4 | 92 | 14 | .4 | *0.03 | *0.005 | *0.5 |
| | **Base** | **9-15-77** | *0.5 | 101 | 0.8 | 88 | 13 | *0.1 | *0.03 | *0.001 | *0.5 |
| | **Base** | **10-1-77** | *0.5 | 19 | 0.9 | 89 | 6 | *0.1 | *0.03 | *0.001 | 0.6 |
| | **Base** | **2-8-78** | *0.5 | 3 | *0.5 | 67 | 1 | *0.1 | *0.03 | 0.003 | *0.5 |
| | **Storm** | **6-19-78** | 1.3 | 58 | 240 | 112 | 28 | 14 | 1.0 | 0.023 | 1.2 |
| **Alamo Canyon** | **Base** | **9-1-77** | *0.5 | 87 | 0.6 | 80 | 11 | *0.1 | *0.3 | *0.001 | *0.5 |
| | **Base** | **10-6-77** | *0.5 | 20 | *0.5 | 85 | 5 | 0.1 | *0.3 | 0.002 | *0.5 |
| | **Base** | **6-2-77** | *0.5 | 6 | *0.5 | 95 | 1 | *0.1 | *0.3 | *0.001 | *0.5 |
| **Capulin Canyon** | **Storm** | **8-17-77** | 0.8 | 112 | 3.7 | 52 | 20 | 1.2 | *0.3 | *0.001 | *0.5 |
| | **Base** | **9-9-77** | *0.5 | 65 | *0.5 | 72 | 13 | *0.1 | *0.3 | *0.001 | *0.5 |
| | **Base** | **4-30-78** | *0.5 | 5 | *0.5 | 81 | 1 | *0.1 | *0.3 | *0.001 | *0.5 |
| | **Base** | **11-30-78** | *0.5 | 6 | *0.5 | 56 | 7 | *0.1 | *0.3 | *0.001 | *0.5 |

*Aquatic Invertebrates*

Jacobi (1992) surveyed the stream benthos at three sites in the Santa Fe National Forest, located in the Jemez Mountains adjacent to Bandelier. The survey was designed to establish a baseline biological condition to gauge future impacts of multiple uses of the national forest such as cattle grazing and timber cutting. The three streams in the Jemez Mountains contained an abundance of species of stoneflies, mayflies (including the acid-sensitive *Baetis* genus), caddisflies, true flies, beetles and some mollusks. No chemical data were provided. We would not expect any change in benthic densities or drift rates of aquatic invertebrates in response to deposition. Assuming that water quality in Bandelier is similar in streams found in the Santa Fe National Forest, we do not expect to see invertebrates communities respond to either current or future deposition pH. The buffering capacities of streams in the Jemez Mountain region are high and therefore, we do not expect acidification of these waters, even under higher loading scenarios. We do not have information on how streams might respond to increases in N loading in deposition.

### *Amphibians*

The following amphibian species have been recorded in Bandelier (Degenhardt 1975): Jemez mountain salamander (*Plethodon neomexicanus*), red-spotted toad (*Bufo punctatus*), Woodhouse's toad (*Bufo woodhousii*), canyon tree frog (*Hyla arenicolor*), and bullfrog (*Rana catesbeiana*). A species list provided by Fleisher (1978) adds the following amphibian species: tiger salamander (*Ambystoma tigrinum*), New Mexico spadefoot toad (*Spea mutiplicata*), leopard frog (*Rana pipiens*), and chorus frog (*Pseudacris triseriata*). Larvae of some of these species were observed in temporary pools found on the Monument. The bullfrog is an exotic species that requires deeper, permanent water for breeding and so appears to be limited to habitats along river edges.

There are data from the eastern U.S. that link acidic soils and surface waters with effects on toad, frog, and salamander life history stages (Baker et al. 1990). However, the pH levels that appear to affect amphibian breeding success in the eastern U.S. are considerably lower (less than pH 5.5) than any observed pH of streams or ponds in the Colorado Plateau region (pHs in the range of 7.0-8.0).

### *Fish*

In 1990-91 researchers sampled fish fauna at sites in Los Frijoles Creek (adjacent to park headquarters), the headwaters of Los Frijoles and Capulin creeks, and the Rio Grande between Otowi Bridge and Cochiti Lake. (Platania 1992). Table 4-8 lists the fish species collected in the area (Post 1983). During the 1990-91 sampling the most commonly observed species were flathead chub (*Hybopsis gracilis*) and longnose dace (*Rhinichthys cataractae*), both native species found in the mainstem of the Rio Grande. Two of the four stream drainages sampled in Bandelier yielded fish species, exclusively introduced salmonids (brook, brown, and rainbow trout).

Data from field surveys and experiments conducted in the eastern U.S., Canada, and Scandinavia have identified both salmonid species and cyprinids as being sensitive to both chronic and episodic acidification (Baker et al. 1990; Dennis 1995; Wigington et al. 1996). However, fish responses to acidic episodes were observed only when pHs dropped below 5.5 and aluminum concentrations exceeded 150 µg/L. These conditions are unlikely to be observed in either the headwater streams or Rio Grande in New Mexico.

Table 4-8. Scientific and common names of fish in Bandelier National Monument and adjacent drainages (Platania 1992).

| Common Name | Latin Name |
|---|---|
| Rainbow trout | Onchorhynchus mykiss |
| Brown trout | Salmo trutta |
| Brook trout | Salvelinus fontinalis |
| Common carp | Cyprinus carpio |
| Rio Grande chub | Gila pandora |
| Flathead chub | Hypobsis gracilis |
| Red shiner | Notropis lutrensis |
| Fathead minnow | Pimephales promelas |
| Longnose dace | Rhinichthys cataractae |
| River carpsucker | Carpiodes carpio |
| White sucker | Catostomus commersoni |
| Black bullhead | Ictalurus melas |
| Channel catfish | Ictalurus punctatus |
| Mosquitofish | Gambusia affinis |
| Green sunfish | Lepomis cyanellus |
| Bluegill | Lepomis macrochirus |
| Largemouth bass | Micropterus salmoides |
| White crappie | Pomoxis annularis |

## Recommendations for Future Monitoring and Research

General recommendations for Class I NPS areas of the Colorado Plateau are provided in Chapter 14. We recommend that NADP and IMPROVE sampling be continued and:

- Continuous ozone sampling be reinstated. The limited information available on ozone at Bandelier indicates levels are commonly higher than on much of the Colorado Plateau, and regional and local air masses that affect Bandelier probably relate poorly to ozone concentrations sampled at Mesa Verde.

- A survey should be conducted to examine for signs of visible injury of leaves from ozone.
- A survey of the chemistry of small streams should be conducted. They are probably well buffered with respect to acidification, but this should be confirmed. If the surface water had moderately low acid neutralizing capacity (less than 200 μeq/L), then a long-term monitoring program should be established and maintained for wet deposition inputs and surface water quality.
- The larger streams in Bandelier have been monitored, and are high in ANC; deposition should not lead to acidification. However, chemistry of these streams will respond to changes in soil chemistry that result from wildfires and prescribed burns. The Monument staff should monitor changes in stream water quality following these fires to determine the changes in mobilization of nitrate, sulfate, and base cations that accompany rainfall episodes. This is important to allow a determination of water quality changes that could be traced to changes in deposition vs. land use changes, such as fires.
- The Monument is a participant in the USGS NAWQA program, and we recommend that the natural resources staff review stream water quality data with the USGS researchers on a regular basis to determine if water quality changes are occurring that might signal the need to more intensive sampling and analysis.

## Monument Summary

Visibility is currently the only AQRV known to be impacted by pollution, as with the other NPS Class I areas of the Colorado Plateau. Current levels of pollution in north-central New Mexico are high enough to produce haze, obscuring the important vistas of the Monument. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Bandelier National Monument.

Little information has been collected on air pollution effects on the Monument's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 5. Black Canyon of the Gunnison National Monument

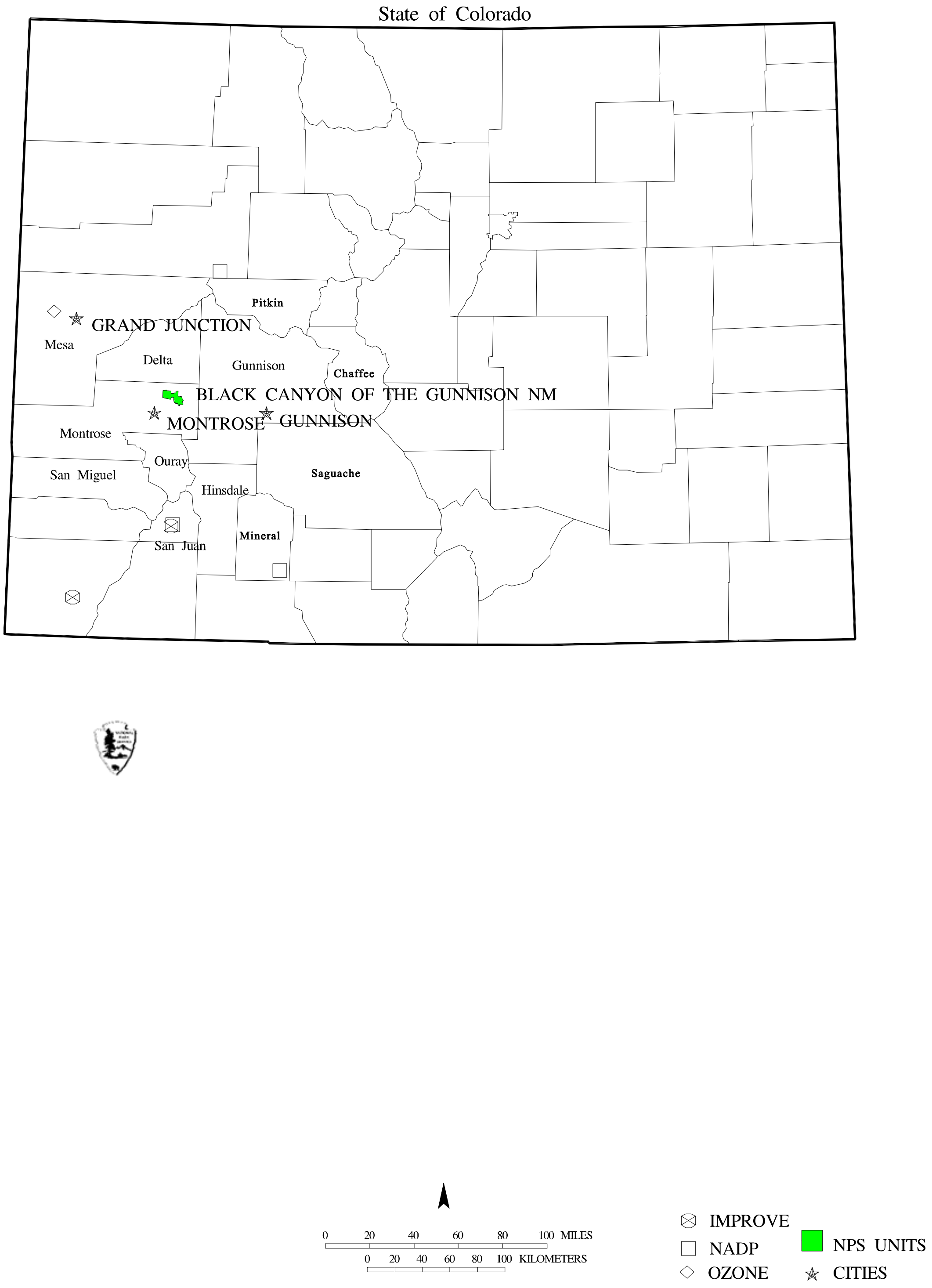
## Introduction

Black Canyon of Gunnison National Monument was added to the National Park System in 1933 and today encompasses 8,407 ha, with all but 50 ha under Federal ownership (Figure 5-1). Today, 4,526 ha inside the Monument are protected as wilderness. Elevation ranges from 1660 m on the Gunnison River where it leaves the Monument to 2755 m on the North Rim. The Monument is located in west-central Colorado, about 35 km east of Montrose, on the central eastern most edge of the Colorado Plateau. The Black Canyon of the Gunnison is 85 km long, but only 18 km of the gorge lies within Black Canyon of Gunnison National Monument. The gorge averages 600 m deep with a maximum depth of 740 m. The Monument was created to protect the natural wonders of a canyon that has the "greatest combination of depth, narrowness, sheerness of any canyon in North America."

### *Geology and Soils*

The geological history of the Black Canyon of the Gunnison is complex, with some formations dating back almost 2 billion years. Most of the exposed rock on the walls of the canyon are schist and gneiss that date to the Precambrian Era, similar to those exposed in the Grand Canyon in Arizona. These Precambrian strata experienced several cycles of burial by sediment and erosion of the resulting sedimentary rock. Only the sedimentary caps from the Triassic and Jurassic Periods remain, and these can be seen on the northeast rim region of the Canyon. During the Cretaceous Period, deposition during the advance and subsequent retreat of the Cretaceous Seaway produced Dakota Sandstone that caps mesas of the Monument, as well as the Mancos Shale exposed to the west of the Canyon. At the end of the Cretaceous, mountain building forces uplifted and tilted the region, and volcano activity in the Tertiary Period modified and shaped the landscape and the course of the ancestral Gunnison River. Eventually, the southern arc of a depressed ring-like syncline became the path of what is today the Gunnison River. In the past 2 million years the Gunnison River has cut through these Tertiary Period volcanic and Mesozoic Era sedimentary deposits and then into the harder Precambrian rock that underlies the region (Chronic 1988).

Figure 5-1. Location of Black Canyon of the Gunnison National Monument.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

Soils vary across the Monument, determined in large part by geologic substrate (mostly volcanic or sedimentary). About 80% of the soils are Argiborolls and Cryoborolls (cold soils with a surficial layer high in organic matter and a deeper layer enriched in clay). In the southwestern portion of the Monument, Haplargids (clayey, dry soils) and Torriorthents (hot, poorly developed soils) are common.

### *Climate*

The Black Canyon of Gunnison National Monument lies in the transition zone between the semidesert plateau and temperate montane climate zones. Mean annual precipitation is about 350 mm while temperatures range from -8 $^{o}$C in the winter to over 30 $^{o}$C in the summer.

### *Vegetation*

Most of the Monument is characterized by a dwarf tree/deciduous shrub brushland that includes Gambel oak (*Quercus gambelii*) and serviceberry (*Amelanchier alnifolia*), with lesser amounts of mountain mahogany (*Cercocarpus montanus*), sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus* spp.). The Pinyon (*Pinus edulis*)/juniper (*Juniperus utahensis*) community also contains the previously mentioned species and Morman tea (*Ephedra viridis*), as well as several species of grasses and forbs. A third dominant plant community in the Monument is the inner-canyon-slope community, composed of some brushland species (including some Douglas-fir (*Pseudotsuga menziesii*) and aspen (*Populus tremuloides*)) and a greater abundance of other shrubs such as fendlerbush (*Fendlera rupicola*), *Rosa* spp., rock spirea (*Holodiscus dumosus*), snowberry (*Symphoricarpos* spp.), currant and gooseberry (*Ribes* spp.) and chokecherry (*Prunus virginiana*). There are no known Threatened and Endangered Plant Species (Threatened and Endangered Species Information Institute 1993) or NPS species of concern. Species lists for Black Canyon of the Gunnison are provided in NPFlora for vascular plants and NPLichen and Wetmore (1983) for lichens.

## Air Quality

Air quality monitoring for Black Canyon of the Gunnison consists of data from 1995 and 1996 for ozone (passive sampling), and camera monitoring of visibility from February 1985 through December of 1993.

### *Emissions*

Table 5-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 12 counties surrounding Black Canyon of the Gunnison. The major source of $SO_x$ in Mesa County is the Cameo Plant of Public Service Company. No information is available to relate these emissions to local air quality at Black Canyon of the Gunnison, or to apportion the air quality impairment of Black Canyon of the Gunnison to local and regional sources. These emission rates are similar to other regions of the Colorado Plateau that are removed from major urban centers. The only major local point source of pollution is a Louisiana Pacific wafer board plant in Olathe. Emissions from this plant may reduce visibility within the Monument, but no quantitative assessment has been made.

Table 5-1. 1994 Emissions (tons/day) for counties surrounding Black Canyon of the Gunnison National Monument (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Chaffee, CO | 26.93 | 0.63 | 3.06 | 7.75 | 13.52 | 0.51 |
| Delta, CO | 46.97 | 1.52 | 5.89 | 11.94 | 65.41 | 0.59 |
| Gunnison, CO | 19.17 | 2.16 | 2.02 | 31.01 | 11.30 | 0.24 |
| Hinsdale, CO | 1.56 | 0.38 | 0.13 | 5.00 | 0.69 | 0.02 |
| Mesa, CO | 118.43 | 2.94 | 25.60 | 32.81 | 196.73 | 8.98 |
| Mineral, CO | 2.75 | 0.31 | 0.25 | 6.42 | 1.37 | 0.03 |
| Montrose, CO | 49.71 | 2.34 | 6.56 | 22.03 | 95.16 | 1.90 |
| Ouray, CO | 5.50 | 0.49 | 0.62 | 4.81 | 19.82 | 0.07 |
| Pitkin, CO | 19.87 | 0.46 | 2.81 | 6.2 | 10.13 | 0.25 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Saguache, CO | 10.52 | 1.94 | 1.23 | 26.26 | 6.05 | 0.12 |
| San Juan, CO | 2.04 | 0.13 | 0.26 | 1.53 | 13.46 | 0.03 |
| San Miguel, CO | 11.48 | 0.74 | 1.32 | 10.62 | 45.24 | 0.11 |

### *Air Pollutant Concentrations and Atmospheric Deposition*

Almost no monitoring of air concentrations has occurred at Black Canyon of the Gunnison. The concentration of ozone (using a passive sampler) in the summer of 1995 averaged 44 ppb on a weekly basis, with a maximum weekly average of 53 ppb.

In general, air chemistry for Black Canyon of the Gunnison may be similar to that of Mesa Verde (Chapter 11), and the NADP deposition data for Mesa Verde may be the most representative for Black Canyon of the Gunnison National Monument. However, the air shed for Black Canyon of the Gunnison probably differs enough from that of Mesa Verde that on-site monitoring of deposition rates would be useful.

### *Visibility*

A camera was used at Black Canyon of the Gunnison. The Monument is not an IMPROVE site, so no compilation of measured extinction or reconstructed extinction are available. As with air chemistry, visibility may be most similar to Mesa Verde National Park (Chapter 11).

## Sensitivity of Plants

No visible signs of air pollution injury have been reported for vegetation in or near Black Canyon of the Gunnison. Only a few of the Monument's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Monument. Based on the ozone concentrations required to affect very sensitive plants (such as aspen), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ across the Colorado Plateau are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality

Black Canyon of the Gunnison National Monument is adjacent to the Curecanti National Recreation Area, with the Gunnison River flowing first through Curecanti National Recreation Area, via a series of reservoirs, then entering the Black Canyon of the Gunnison. Water quality sampling has been conducted in Curecanti National Recreation Area, both in the major reservoir (Blue Mesa Lake) and in a number of side streams draining into the Gunnison River (Long et al. 1995). Threats to these surface waters are associated with activities that increase turbidity and sediment loads, such as recreation, grazing and leakage from septic tanks. During these water quality surveys, ANC was not measured. The sensitivity of these waters can be inferred from pH and specific conductance [specific conductance is a measure of the total dissolved solids in waters. Conductivity is reported as either micro-ohms per centimeter or micro-Siemens per centimeter. These are equivalent values.] Water quality surveys within the adjacent Curecanti National Recreation Area indicate that there is a potential for non-point source runoff of N to streams in this area. We recommend there be an examination of the data sets to determine if excess nitrate is currently found in streams, especially during spring runoff. If high nitrate levels are found, there should be a watershed-level analysis of the sources of that N.

The lowest readings for both of these parameters were in Blue Creek, monitored in 1993 as having a range of pH values of 6.7-8.0 and a range of conductivities of 35-119 μS/cm, and Curecanti Creek, monitored in 1993 as having pH values of 6.7-8.0 and a range of conductivities of 35-107 μS/cm. This range of values indicates that even the tributary streams are well-buffered and unlikely to be affected by atmospheric deposition.

## Recommendations for Future Monitoring and Research

General recommendations for Class I NPS areas of the Colorado Plateau are given in Chapter 14. No air quality monitoring occurs at Black Canyon of the Gunnison National Monument. Black Canyon of the Gunnison may be close enough to Mesa Verde to be represented by Mesa Verde's air quality patterns, but the intervening San Juan Mountains may cause substantial differences in the flow of air masses between these Class I areas. Therefore, we recommend:

- On-site monitoring of air quality be developed, including as a minimum some measurement of ozone concentrations (by continuous or passive methods) and atmospheric deposition.
- Acidification of surface waters in the Monument is unlikely due to the large solute loads in streams. We recommend that the Monument staff work with the USGS-NAWQA staff to determine if sensitive bedrock types are found within the Monument that might contain streams with low ANC. An extensive stream survey in these areas would be useful to determine the status of headwater streams. We do not expect that N deposition poses a threat to the streams in the Monument, but streams could be monitored to verify that concentrations of nitrate do not reach unexpectedly high levels.

## Monument Summary

Black Canyon of the Gunnison National Monument lacks any substantial monitoring program, so it is difficult to determine any AQRV impacts. We suspect that visibility has been impaired by pollution on a substantial portion of days, as with the other Class I NPS areas of the Colorado Plateau. Current levels of pollution in southwestern Colorado are high enough to produce haze and obscure the important vistas at Mesa Verde National Park, and probably at Black Canyon of the Gunnison National Monument. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Black Canyon of the Gunnison National Monument.

Little information has been collected on air pollution effects on the Monument's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations across the Colorado Plateau are too low to affect plants.

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# Chapter 6. Bryce Canyon National Park

## Introduction

Bryce Canyon National Park was added to the USDA system of National Monuments in 1923. The Monument became a National Park in 1928 when responsibility shifted to the National Park Service. Bryce Canyon National Park encompasses 14,508 ha, almost all federally owned (Figure 6-1). The Park lies in south central Utah along an escarpment of the Paunsaugunt Plateau and is therefore not a true canyon. Bryce Canyon is within Kane and Garfield Counties, and is bordered by the Dixie National Forest. The Park was originally established to protect the natural beauty of the area, specifically the naturally sculpted multicolored amphitheaters and rock "hoodoo" formations. The Presidential Proclamation that established the original Monument reads:

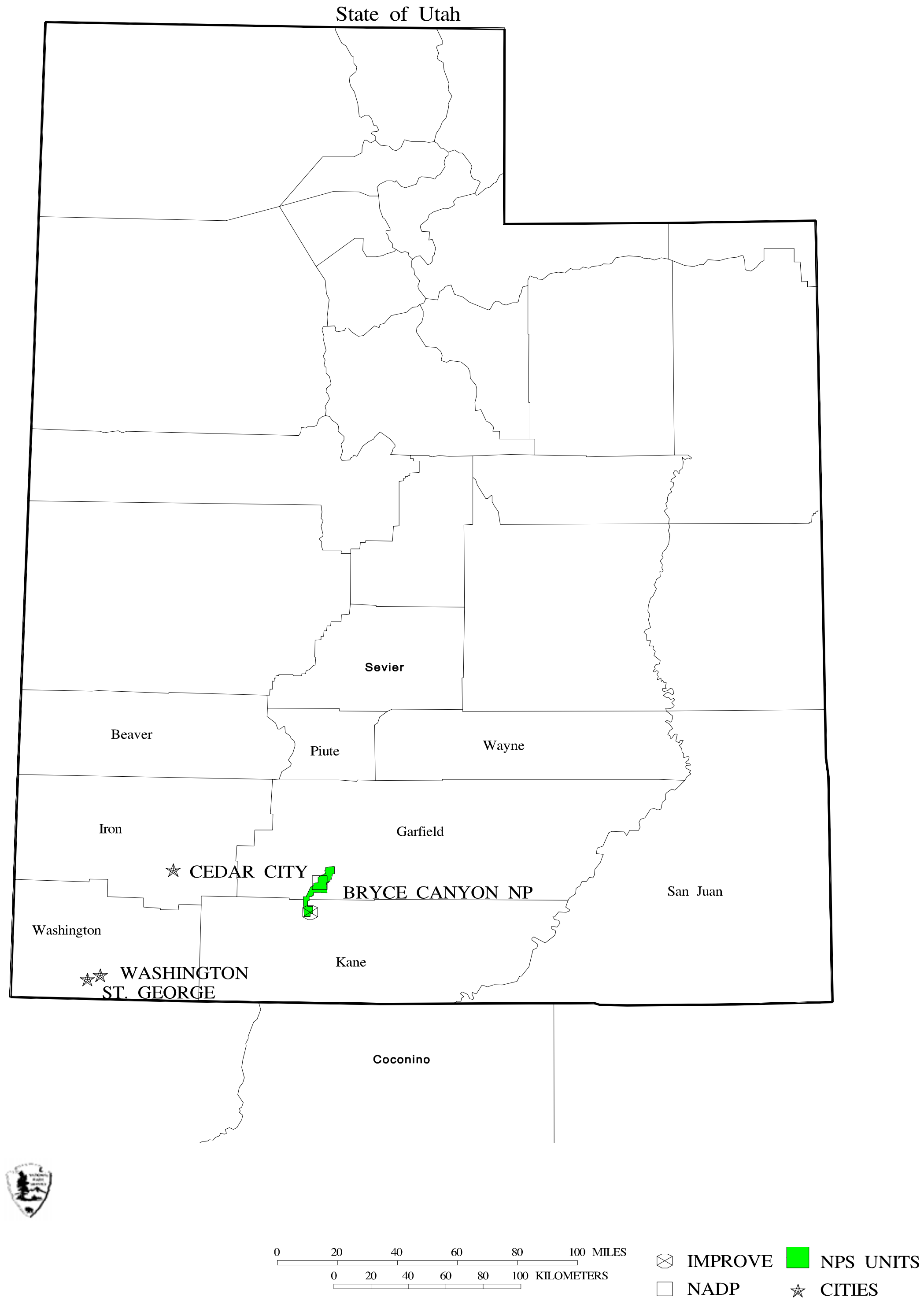
> "certain lands within the Powell National Forest in the State of Utah, known as Bryce Canyon, are of unusual scenic beauty, scientific interest and importance, and it appears that the public interest will be promoted by reserving these areas with as much land as may be necessary for the proper protection thereof as a National Monument".

Elevations in the park range from 2018 m at the north end of the Park to 2775 m at the south end of the Park.

### *Geology and Soils*

The geology of Bryce Canyon National Park is relatively simple. The rocks from the Paleozoic and early Mesozoic Eras that underlie the region are not exposed within Bryce Canyon. During the Cretaceous Period, the region was gradually uplifted and the Cretaceous Seaway receded. Uplift processes raised the Rocky Mountains to the east and the Sevier Mountains to the west, developing a landlocked, lake-filled basin that accumulated sediments washed in from the surrounding mountains. The Claron Formation that comprises the majority of the escarpment at Bryce Canyon National Park developed from these lake deposits of silty limestone and mudstone. During the Oligocene and Miocene Epochs, the Colorado Plateau experienced extensive volcanism and uplift that resulted in faulting, intrusions and elevated rates of erosion. This period saw the formation of the Colorado River. Later, the Paria River developed and carved into the Paunsaugunt Plateau, producing the intricate gullies, canyons and "hoodoos" of Bryce Canyon (Chronic 1988).

Figure 6-1. Location of Bryce Canyon National Park.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

Soils in the Park are largely derived from the Claron Formation and are therefore calcareous, with varying amounts of silt and clay and some sands cemented by carbonates, fine grained and usually easily eroded. Generally there is little topsoil and the fine textured soils drain poorly and hold water.

### *Climate*

Bryce Canyon National Park averages about 390 mm of annual precipitation, with greater amounts at the higher southern end, and lower amounts at the lower, northern end. Temperature patterns show the opposite pattern, with cooler temperature at the higher elevations. At the Park headquarters, temperatures range from -8 $^{o}$C in the winter to over 31 $^{o}$C in the summer. Precipitation often comes in torrential downpours and in heavy snowfall; the winter snowpack typically exceeds 1.5 m.

### *Vegetation*

The plateau is dominated by two major forest types. In the north end of Bryce Canyon National Park, from about 2,100 m to 2,600 m, ponderosa pine (*Pinus ponderosa*) plant communities dominate. Pines are interspersed with Rocky Mountain juniper (*Juniperus scopulorum*), Utah Juniper (*Juniperus osteosperma)* and a number of shrub and grass species that include green leaf manzanita (*Arctostaphylos patula*), antelope bitterbrush *(Purshia tridentata*), mountain lilac (*Ceanothus integerrimus*), Indian ricegrass (*Achnatherun hymenoides*), mutton grass (*Poa interior*) and mountain muhly (*Muhlenbergia montana*). Limber pine (*Pinus flexilis*) and bristlecone pine *(Pinus longaeva*) occupy some of the sunnier slopes and exposed ridges on the plateau rim. Below the rim, pinyon pine (*Pinus edulis*)/juniper (*Juniperus* spp.) communities occur, with sagebrush (*Artemisia* spp.) and rabbitbrush (*Chrysothamnus* spp.). Above 2,600 m, mixed-conifer communities dominate with Douglas-fir (*Pseudotsuga menzeisii*), white fir (*Abies concolor*), aspen (*Populus tremuloides*) and some blue spruce (*Picea pungens*). In the low light environment of the understory of these forests, common juniper (*Juniperus communis*), snowberry (*Symphoricarpos oreophilus*), creeping barberry (*Berberis repens*), and wild rose (*Rosa woodsii*) are encountered. Weedy exotics include Russian thistle (*Salsola tragus*), Russian knapweed (*Centaurea sp.*), crested wheatgrass (*Agropyron cristatum*), pigweed (*Cycloma sp.*), cheatgrass *(Bromus tectorum*), shepherd's purse (*Capella bursa-pastoralis*), bindweed (*Convolvulus arvensis*), horehound

(*Marrubium vulgare*), and English plantain *(Plantago lanceolata).* There are four NPS species of concern that occur near (but not documented within) Bryce Canyon: *Silene petersonii*, *Cryptantha ochroleuca*, *Penstemon bracteatus* and *Pediomelum pariense* (Threatened and Endangered Species Information Institute 1993). Complete species list for vascular flora are provided by NPFlora as well as by Buchanan and Graybosch (1981), Graybosch and Buchanan (1983), Hallsten and Roberts (1988), Spence and Buchanan (1993) and Peabody (1994). A list for lichen species is provided by Wetmore (1983).

## Air Quality

Air quality monitoring for Bryce Canyon National Park consists of ozone concentrations (passive collector) for 1995 and 1996, NADP monitoring from 1985 to the present, sulfur dioxide measurements from 1988-1992 (except for 1990), and IMPROVE monitoring for visibility from 1988 to the present.

### *Emissions*

Table 6-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 15 counties surrounding Bryce Canyon National Park. The emissions from Coconino County in northern Arizona are higher than from other counties in the area, with the vast majority of $SO_x$ emissions coming from the Navajo Station of the Salt River Project. No information is available to relate these emissions to local air quality at Bryce Canyon National Park, or to apportion air quality impairment at Bryce Canyon to local and regional sources.

Table 6-1. Emissions (tons/day) for counties surrounding Bryce Canyon National Park (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Beaver, UT | 14.9 | 0.7 | 1.7 | 31 | 142 | 0.3 |
| Garfield, UT | 13.7 | 0.6 | 1.5 | 63 | 253 | 0.2 |
| Iron, UT | 36.1 | 0.9 | 3.7 | 39 | 190 | 0.9 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Kane, UT | 14.9 | 0.3 | 1.6 | 44 | 114 | 0.2 |
| Piute, UT | 4.6 | 0.4 | 0.5 | 9 | 8 | 0.1 |
| San Juan, UT | 40.8 | 0.7 | 3.9 | 103 | 405 | 0.5 |
| Sevier, UT | 36.5 | 1.1 | 4.8 | 24 | 58 | 1.3 |
| Washington, UT | 63.7 | 0.6 | 6.5 | 34 | 189 | 0.9 |
| Wayne, UT | 6.3 | 0.6 | 0.7 | 30 | 122 | 0.1 |
| Coconino, AZ | 145.5 | 3.2 | 132.8 | 209 | 659 | 213.2 |

### *Air Pollutant Concentrations*

The concentration of ozone for the summer of 1995 averaged about 46 ppb (based on weekly averages from passive collectors), with a peak weekly average of 53 ppb. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants (Table 6-2).

Table 6-2. Concentrations (ppb) of $SO_2$ (24-hour averages) for Bryce Canyon National Park, measured by IMPROVE filter samplers.

| Year | $SO_2$ |
|---|---|
| 1988 | |
| Mean | 0.0 |
| Max | 0.3 |
| 1989 | |
| Mean | 0.1 |
| Max | 0.5 |
| 1991 | |
| Mean | 0.2 |
| Max | 0.8 |
| 1992 | |
| Mean | 0.1 |
| Max | 0.5 |

### *Visibility*

Bryce Canyon National Park is part of the IMPROVE Monitoring Network. The aerosol sampler began operation in March 1988 and the camera began operation in January 1979. The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period March 1988 through February 1994. The camera is located at Rainbow Point, and the particulate sampler near the Visitors Center. The seasons used throughout this data presentation are: spring = March, April, and May; summer = June, July, and August; autumn = September, October, and November; and winter = December, January, and February.

### Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient ($b_{ext}$) from experimentally determined extinction efficiencies of certain species. The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions.

Table 6-3 provides a summary of the reconstructed extinction from the aerosol sampler data, presented as seasonal and annual 50th and 90th percentile standard visual range for Bryce Canyon National Park. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

Table 6-3. Reconstructed visual range and light extinction coefficients for Bryce Canyon National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentiles, March 1988 - February 1994.

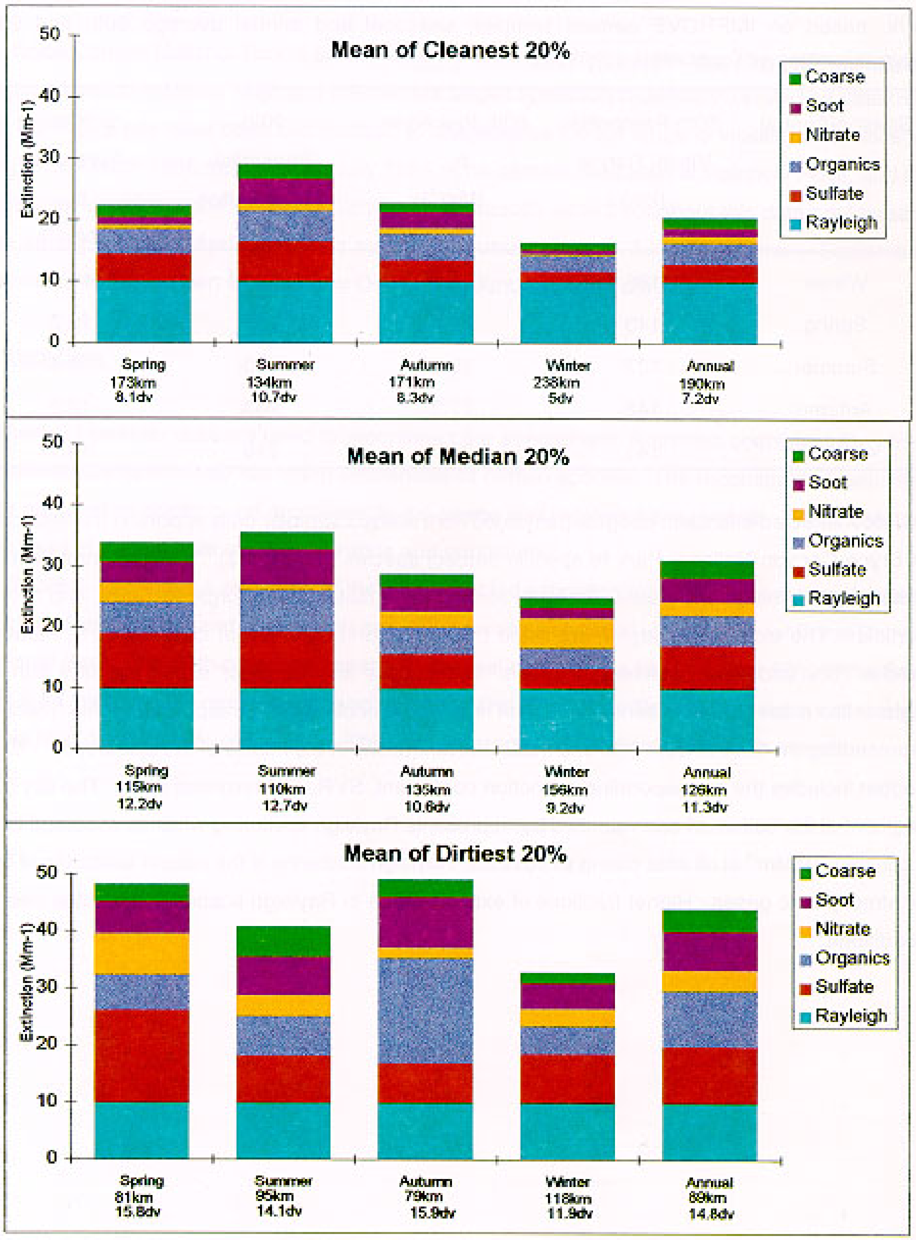
| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 186 | 21.0 | 244 | 16.0 |
| Spring | 143 | 27.4 | 203 | 19.2 |

| | | | | |
|---|---|---|---|---|
| Summer | 127 | 30.7 | 160 | 24.4 |
| Autumn | 143 | 27.3 | 203 | 19.2 |
| Annual | 141 | 27.7 | 216 | 18.1 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Bryce Canyon National Park to specific aerosol species (Figure 6-2). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20%, mean of median 20%, and mean of dirtiest 20% days. The "dirtiest" and "cleanest" signify the days with the highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicates cleaner conditions.

Figure 6-2. Reconstructed extinction budgets for Bryce Canyon National Park, March 1993 through February 1994.

Figure 6-2. Reconstructed extinction budgets for Bryce Canyon NP, March 1993 through February 1994.



Atmospheric light extinction at Bryce Canyon National Park, like many rural western areas, results primarily from aerosols of sulfate, organic compounds, and soot. In pre-industrial times, visibility would vary with patterns in weather, with winds (and the effects of winds on coarse particles), and with fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions, but the cleanest 20% of the days probably approach natural conditions (GCVTC 1996).

## Photographs

Three photos are provided to represent the range of visibility conditions at Bryce Canyon National Park (Figure 6-3). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what the observer sees.

## Visibility Projections

The Grand Canyon Visibility Transport Commission (GCVTC 1996) projected likely visibility for Bryce Canyon National Park through 2040, and the major species responsible for visibility impairment. Reduced emissions from utilities were projected to reduce light extinction by approximately 1 $Mm^{-1}$. Light extinction caused by vehicle emissions was projected to decline until approximately 2005, and then increase through 2040 (Figures 6-4, 6-5). The dirtiest days have more than twice the visibility impairment, and the bulk of the change results from human- related sources. There is some concern that the modeling completed by the GCVTC may not adequately represent the relative contribution of near and far away sources.

Figure 6-3. Photographs representing visibility conditions at Bryce Canyon National Park.

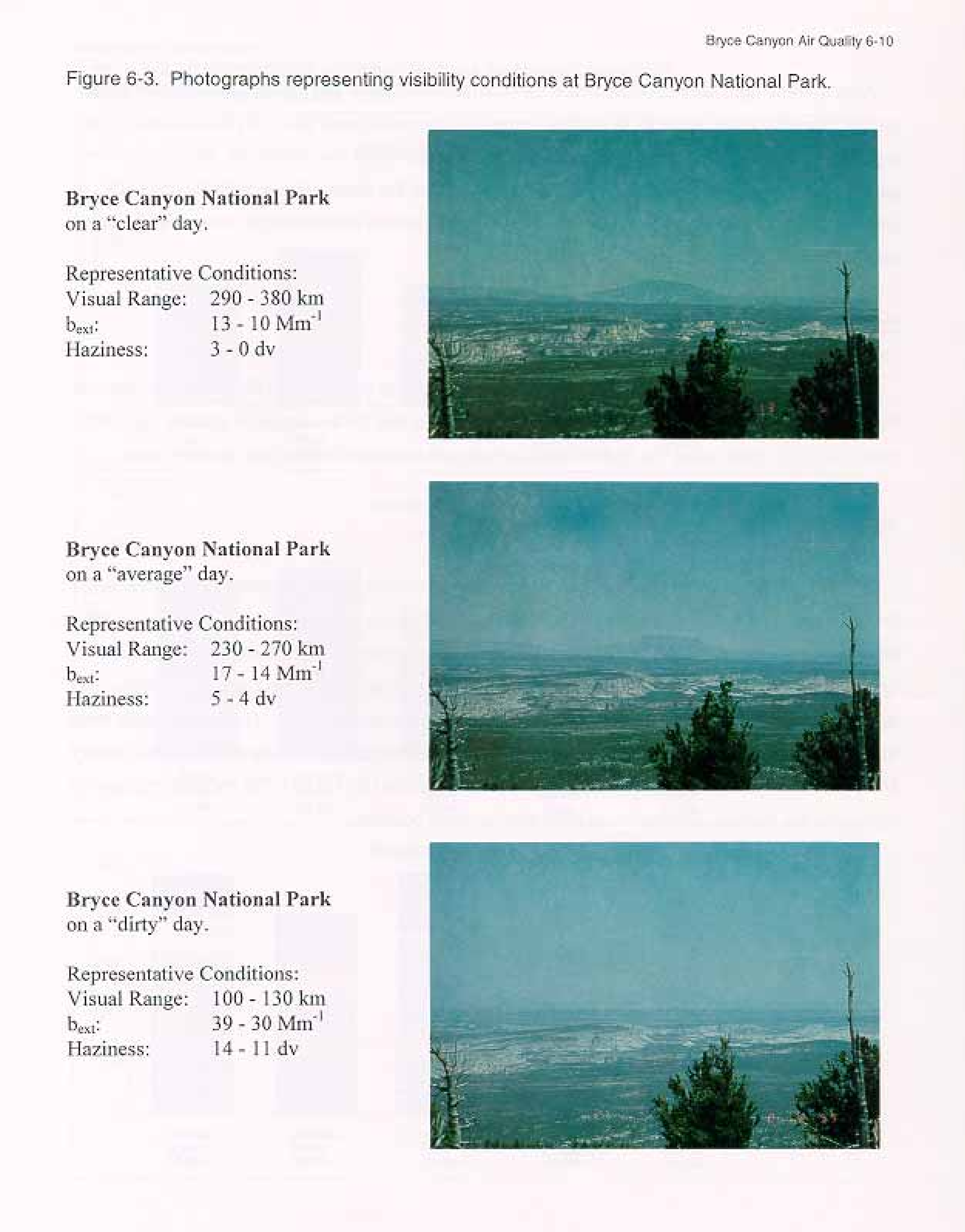


Figure 6-3. Photographs representing visibility conditions at Bryce Canyon National Park.

**Bryce Canyon National Park**
on a "clear" day.

Representative Conditions:

| | |
|---|---|
| Visual Range: | 290 - 380 km |
| $b_{ext}$: | 13 - 10 $\text{Mm}^{-1}$ |
| Haziness: | 3 - 0 dv |

**Bryce Canyon National Park**
on a "average" day.

Representative Conditions:

| | |
|---|---|
| Visual Range: | 230 - 270 km |
| $b_{ext}$: | 17 - 14 $\text{Mm}^{-1}$ |
| Haziness: | 5 - 4 dv |

**Bryce Canyon National Park**
on a "dirty" day.

Representative Conditions:

| | |
|---|---|
| Visual Range: | 100 - 130 km |
| $b_{ext}$: | 39 - 30 $\text{Mm}^{-1}$ |
| Haziness: | 14 - 11 dv |

Figure 6-4. Projected “baseline” light extinction for Bryce Canyon National Park (GCVTC 1996).

Figure 6-4. Projected "baseline" light extinction for Bryce Canyon National Park (GCVTC 1996).

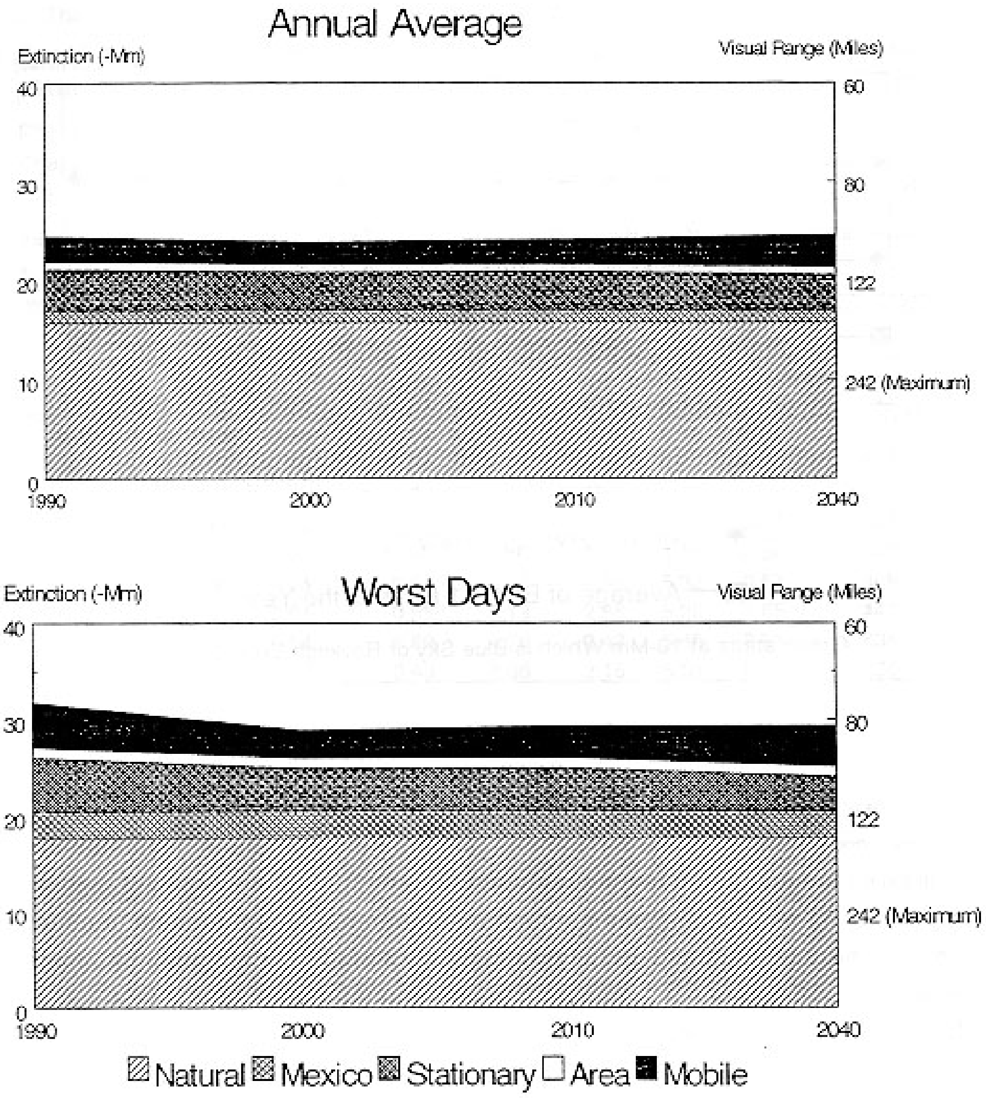
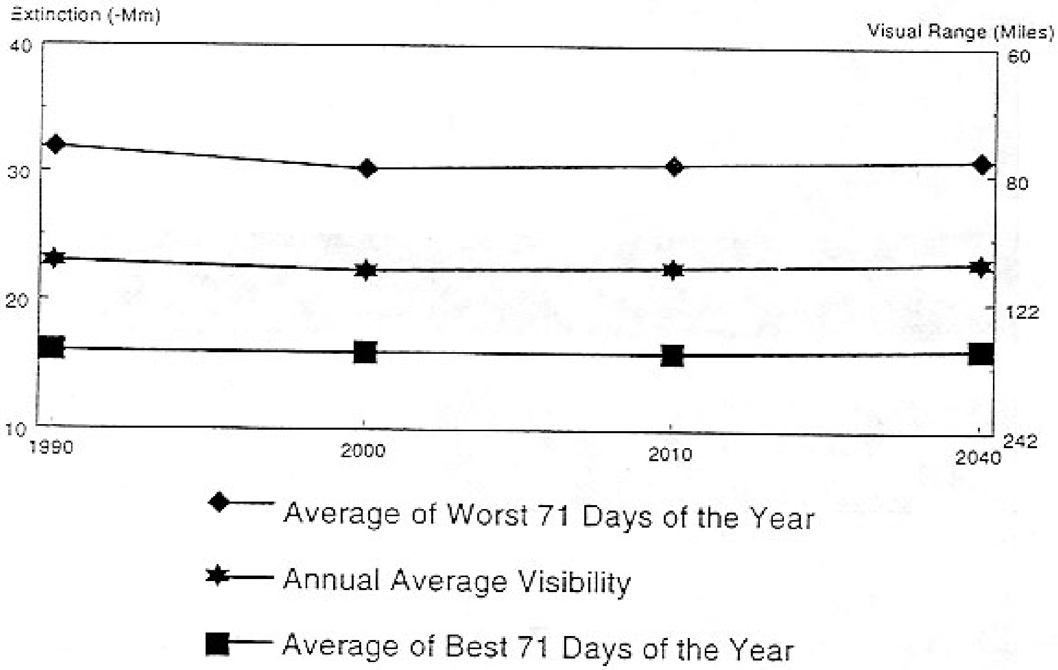


Figure 6-5. Projected “baseline” visibility for Bryce Canyon National Park for good, average, and poor conditions (GCVTC 1996).

Bryce Canyon Air Quality 6-12

Figure 6-5. Projected “baseline” visibility for Bryce Canyon National Park for good, average, and poor conditions (GCVTC 1996).



Graph starts at 10-Mm Which is Blue Sky or Rayleigh Extinction.

### *Atmospheric Deposition*

The rates of atmospheric deposition for Bryce Canyon National Park are quite low (Table 6-4). Precipitation pH averages about 5.3. Deposition of N averages about 1 kg N $ha^{-1}$ $yr^{-1}$, which is slightly higher than the rate of S deposition. The deposition of N and S showed no trend during this period. There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 6-4. Atmospheric deposition for Bryce Canyon National Park (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentration (mg/L) | | | Deposition (kg $ha^{-1}$ $yr^{-1}$) | | | | Conductivity | Precipitation |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | (μS/mm) | (mm/yr) |
| 1985 | 0.07 | 0.64 | 0.71 | 0.27 | 2.46 | 2.72 | 5.19 | 0.75 | 384 |
| 1986 | 0.05 | 0.54 | 0.58 | 0.17 | 1.84 | 1.97 | 5.12 | 0.61 | 340 |
| 1987 | 0.09 | 0.67 | 0.70 | 0.39 | 2.93 | 3.07 | 5.07 | 0.72 | 438 |
| 1988 | 0.07 | 0.88 | 0.78 | 0.22 | 2.77 | 2.45 | 5.17 | 0.74 | 314 |
| 1989 | 0.18 | 1.06 | 0.76 | 0.44 | 2.58 | 1.85 | 5.56 | 0.87 | 244 |
| 1990 | 0.20 | 0.95 | 0.68 | 0.69 | 3.30 | 2.36 | 5.18 | 0.86 | 347 |
| 1991 | 0.14 | 0.90 | 0.64 | 0.51 | 3.31 | 2.35 | 5.32 | 0.67 | 368 |
| 1992 | 0.13 | 0.70 | 0.64 | 0.58 | 3.13 | 2.86 | 5.22 | 0.65 | 447 |
| 1993 | 0.14 | 0.75 | 0.54 | 0.89 | 4.76 | 3.43 | 5.45 | 0.58 | 634 |
| 1994 | 0.14 | 0.88 | 0.67 | 0.45 | 2.86 | 2.18 | 5.01 | 0.81 | 325 |

## Sensitivity of Plants

No signs of air pollution injury have been reported for vegetation in or near Bryce Canyon National Park. Only a few of the Park’s species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants (such as aspen), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

### *Aquatic Invertebrates*

The eastern slope of Bryce Canyon National Park forms a part of the headwaters of the Paria River, a tributary of the Colorado River. The current macroinvertebrate species list for Bryce Canyon includes 13 Orders, with the largest number of species falling into these Orders (Dorr and Weiss 1994):

Ephemeroptera (Mayflies, including *Baetis* spp.),
Plecoptera (Stoneflies),
Coleoptera (Beetles), and
Diptera (True flies, including Chironimids).

Two sites (Mossy Cave and Yellow Creek Swamp) had the highest number of species represented.

### *Amphibians*

An amphibian species list for the park includes the tiger salamander (*Ambystoma tigrinum*), Great Basin spadefoot toad *(Scaphiopus intermontanus)*, and leopard frog (*Rana pipiens*) (Hallows 1982). Specimens have been found in a variety of habitats in the Park, and in livestock ponds and beaver ponds outside the Park. Historic information on amphibian species can be found in Tanner (1930). Surveys in 1929 yielded tiger salamanders and spadefoot toads. These amphibians appear to be reproducing in seeps and springs since there are few permanent water courses in the park.

### *Water Quality Conclusions*

No evidence indicates any threat to water quality or aquatic organisms from air pollution in Bryce

Canyon National Park.

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Bryce Canyon. Continued monitoring of visibility should remain a high priority. Bryce Canyon is higher in elevation than several other NPS areas in southeastern Utah, and inversion layers in winter that affect other parks may not reach the elevation of Bryce; differences in visibility between Bryce and Canyonlands, for example, can provide useful insights to the role of winter inversions in regional air quality (C. Bowman, personal communication). We also recommend:

- measurements of ozone (continuous or passive) be maintained.

We found no information on surface water quality in Bryce Canyon NP. Seeps and springs, and some ephemeral pools are the habitat for both vertebrate and invertebrate fauna. Given the geological substrates, acidification of aquatic systems in the Park is unlikely. However, we recommend:

- baseline water chemical data be collected in habitats where macroinvertebrates and amphibian larvae occur. The suite of measurements could be as simple as pH, ANC, and conductance.

## Park Summary

Bryce Canyon National Park is located in an area where the best visibility in the lower 48 United States occurs. However, current levels of pollution in southern Utah can produce haze and obscure the important vistas of the park and surrounding area. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Bryce Canyon National Park.

Little information has been collected on air pollution effects on the Park’s biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 7. Canyonlands National Park

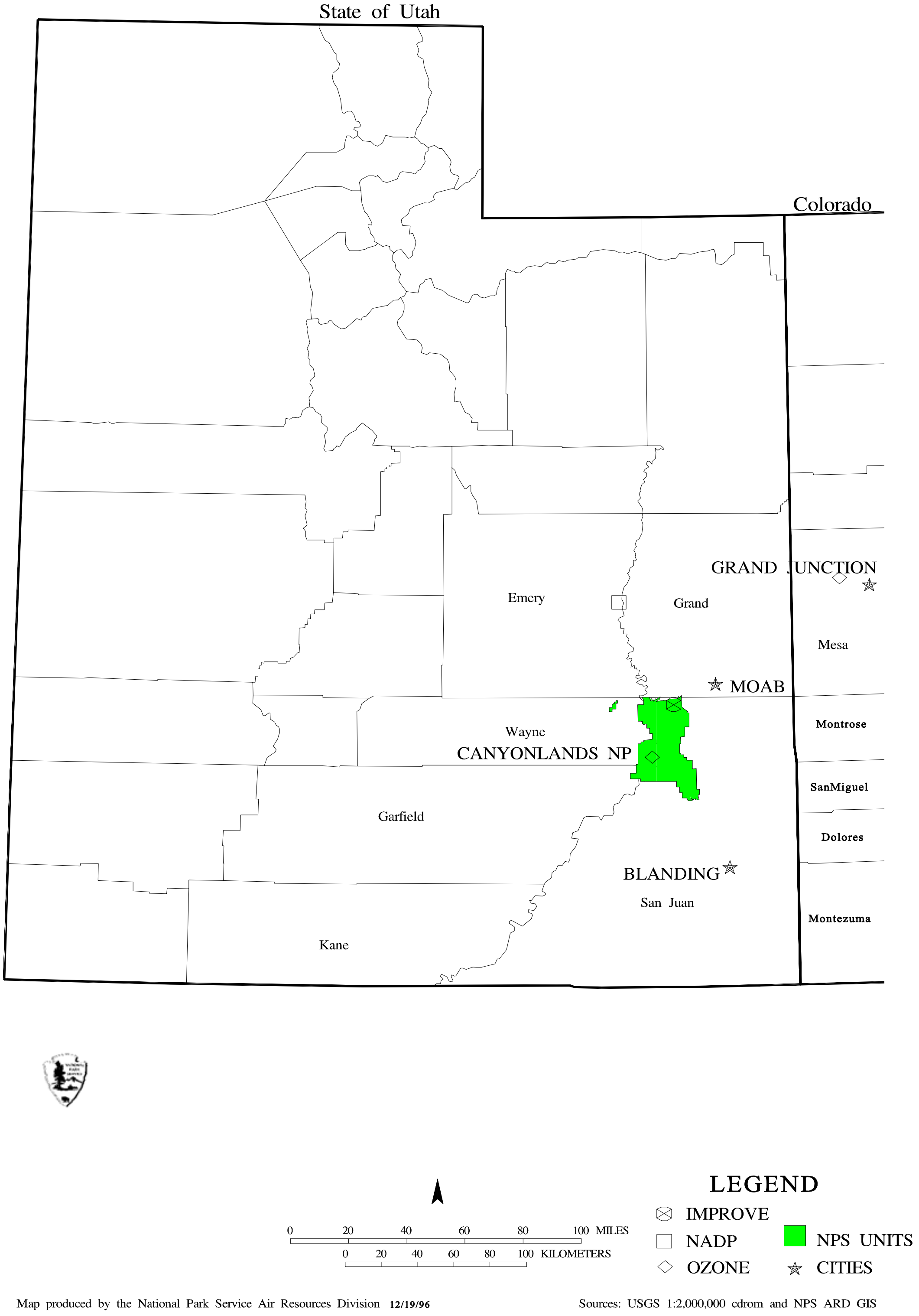
## Introduction

Canyonlands National Park was established in 1964 to “protect a remote region of exceptional scenic quality and archaeological and scientific importance at the confluence of the Green and Colorado rivers in southeastern Utah for inspiration, benefit and use of the public". The Park encompasses 136,670 ha of federally owned land in the high desert region of southeastern Utah (Figure 7-1). Elevations range from 1125 m where the Colorado River leaves the Park in Cataract Canyon to 2170 m at Cathedral Point in the Needles District at the southeastern end of the Park. In addition to the spectacular natural beauty, the Park has many archeological features including prehistoric pictographs and petroglyphs and the remains of several Native American cultures. The Park includes parts of Garfield, Wayne, Grand and San Juan Counties.

### *Geology and Soils*

The oldest formations in Canyonlands National Park date back to the Paleozoic Era, when much of the region was covered by shallow seas. These seas deposited successive layers of marine limestone, sandstone and shale, especially during the Pennsylvanian Period. These seas occasionally became landlocked which resulted in evaporation of sea water and deposition of the evaporites. The overall thickness of these alternating salt and shale layers can exceed 1000 m. During the Permian Period, these basins were filled with alternating layers of sand and pebbles eroded from surrounding highlands, and marine deposits (sands, shales, and limestone) from periods when shallow seas advanced over the landscape. The Mesozoic Era brought large scale changes in climate and depositional environments. During the Triassic Period, uplifts in Colorado provided the energy for the alluvial transport of material, covering much of the Canyonlands area with alluvial deposits from the new high country to the east. During the Jurassic Period, mountain building events to the west blocked the flow of moist air over the region, producing a desert/dune environment with wind-deposited sand. These petrified sand dunes comprise the massive cross-bedded sandstone layers that characterize the Canyonlands region. During the Cretaceous Period, seas advanced again and new strata of marine sands, shales and limestones were deposited. These Cretaceous deposits were later completely eroded away in the region of Canyonlands National Park and surrounding areas. Alluvial deposits of the Tertiary Period eroded away, with no

Figure 7-1. Location of Canyonlands National Park.



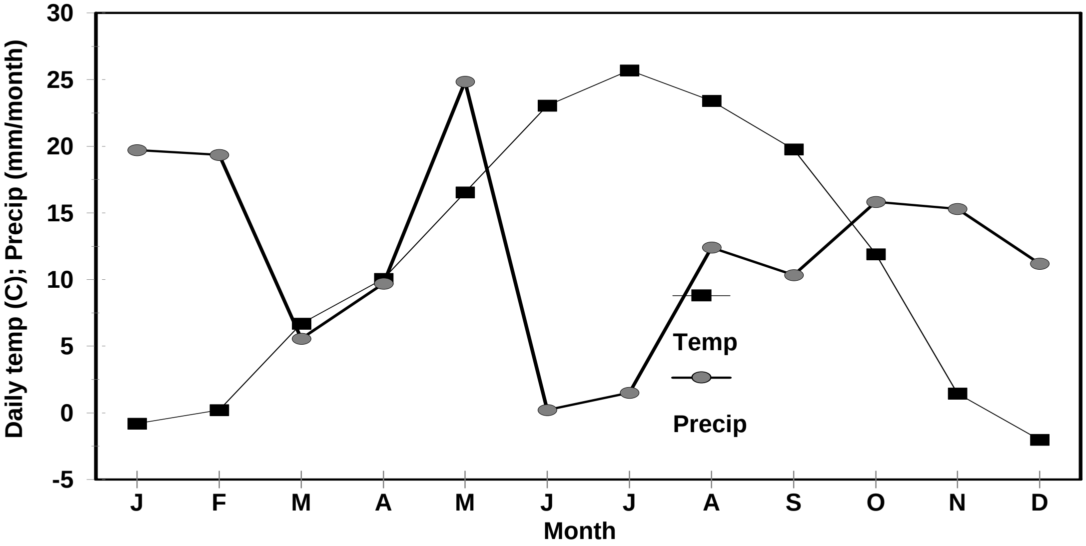
Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

evidence of their presence in the region. From about 70 to 60 million years ago, the Laramide Orogeny began compressing the Colorado Plateau from the west, uplifting the region and producing monoclines. In the middle Tertiary, the massive uplift of the Rockies provided additional energy to the erosional and alluvial forces that were dissecting the Plateau. The major rivers, the Colorado and Green, set their paths and began to deeply incise the Colorado Plateau (Chronic 1988). In general Canyonlands National Park is covered by bedrock or slightly modified bedrock; soils are sandy and weakly developed.

### *Climate*

The arid climate is characterized by hot, dry summers and cool to cold winters. The Park receives only about 175 mm/yr, with most of the moisture falling during the winter and late summer. Daily temperatures average 25 $^{o}$C in the middle of summer, and -2 $^{o}$C in winter.



Winds show little seasonal trends; most air comes from the southeast or northwest (Figure 7-3).

Figure 7-3. Wind rose for Canyonlands National Park, 1992-1996.

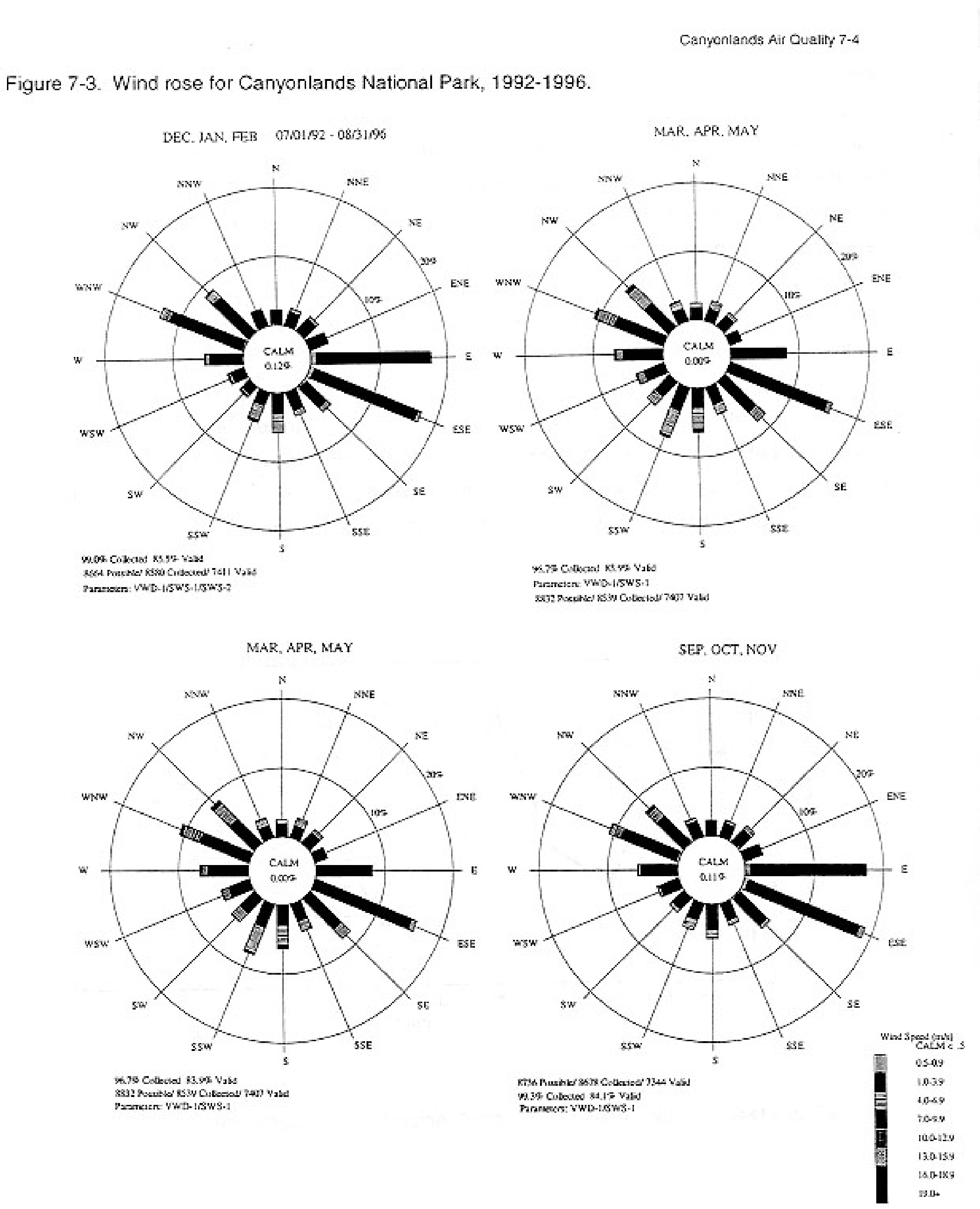


Figure 7-3. Wind rose for Canyonlands National Park, 1992-1996.

DEC, JAN, FEB 07/01/92 - 08/31/96

99.0% Collected 85.5% Valid
8664 Possible/ 8580 Collected/ 7411 Valid
Parameters: VWD-1/SWS-1/SWS-2

MAR, APR, MAY

96.7% Collected 83.9% Valid
Parameters: VWD-1/SWS-1
8832 Possible/ 8539 Collected/ 7407 Valid

MAR, APR, MAY

96.7% Collected 83.9% Valid
8832 Possible/ 8539 Collected/ 7407 Valid
Parameters: VWD-1/SWS-1

SEP, OCT, NOV

8736 Possible/ 8678 Collected/ 7344 Valid
99.3% Collected 84.1% Valid
Parameters: VWD-1/SWS-1

Wind Speed (m/s)
CALM < .5
0.5-0.9
1.0-3.9
4.0-6.9
7.0-9.9
10.0-12.9
13.0-15.9
16.0-18.9
19.0+

### *Vegetation*

As with neighboring Arches, geologic substrate and soil type greatly influence the type and distribution of plant communities in Canyonlands National Park (Table 7-1). The dominant vegetative cover types in order of importance are pinyon (*Pinus edulis*)/ juniper (*Juniperus osteosperma*) community which covers about 1/3 of the Park, and includes blackbrush (*Coleogyne ramosissima*), fragrant sumac (*Rhus aromatica*), singleleaf ash (*Fraxinus anomala*), and serviceberry (*Amelanchier utahensis*); blackbrush/Mormon tea (*Ephedra* spp.) shrublands; snakeweed (*Gutierrezia sarothrae*)/ saltbush (*Atriplex* spp.)/Mormon tea shrublands; and galleta (*Pleuraphis jamesii*)/ Indian ricegrass (*Achnatherun hymenoides)* semi-desert grasslands. Large areas of Canyonlands National Park are covered by mixed grasses and microbiotic crusts. Complete species lists for vascular plants in Canyonlands National Park can be found in NPFlora and Welsh (1970), while NPLichen provides a listing of lichen species. There are no known Threatened and Endangered Plant Species or NPS species of special concern (Threatened and Endangered Species Information Institute 1993).

Table 7-1. Distribution of major communities in Canyonlands National Park.

| Vegetation type | Landform | Percent of Park area |
|---|---|---|
| Snakeweed/Saltbush | Steep talus | 13 |
| Snakeweed/Mormon tea | Broken slope | 11 |
| Saltbush/cheat grass | Benchland | 4 |
| Indian ricegrass/needle&thread grass/blue grama | Mesa | 2 |
| Galleta/Indian ricegrass | Bench/terrace/graben | 9 |
| Blackbrush/Mormon tea/Galleta | Terrace | 20 |
| Sagebrush/saltbush | Alluvial bench | 2 |
| Tamarisk/willow | Riparian | 1 |
| Pinyon/juniper/cottonwood | Canyon/near riparian | 4 |

| | | |
|---|---|---|
| Pinyon/juniper | Upland | 34 |

## Air Quality

Monitoring of air quality in Canyonlands National Park has included various periods of sampling for ozone and $SO_2$, and IMPROVE visibility monitoring. The nearest NADP site is Green River, Utah.

### *Emissions*

Table 7-2 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 11 counties surrounding Canyonlands National Park. Most of the high emission of $SO_x$ for Emery County come from the Huntington and Hunter Pacificorp plants. Eatough et al. (1996) apportioned the $SO_x$ in Canyonlands to emission sources over a 3-month period from January through March in 1990, based on “fingerprints” of ratios of compounds in the air, and air mass trajectories. For example, emissions from coal-fired power plants had high ratios of spherical aluminosilicate particles to sulfate, but very low ratios of arsenic to sulfate. Air from Arizona was characterized by low ratios of these aluminosilicate particles to sulfate, and high ratios of arsenic to sulfate. They concluded that $SO_x$ in Canyonlands National Park derived from a wide range of regional sources rather than from a dominant source; about 37% (during a 21 day period) came from the southwest, 20% from the south/southeast, 19% from the north/northeast, and 23% from the northwest. Eatough et al. (1996) concluded that the major sources of $SO_x$ were from the southwest, while major sources of particulate sulfate were from the southeast.

Table 7-2. Emissions (tons/day) for counties surrounding Canyonlands National Park (Radian 1994)

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Emery, UT | 40 | 1 | 114 | 56 | 273 | 51.7 |
| Garfield, UT | 14 | 1 | 1 | 63 | 253 | 0.2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Grand, UT | 17 | 0 | 2 | 47 | 185 | 0.2 |
| Kane, UT | 15 | 0 | 2 | 44 | 114 | 0.2 |
| San Juan, UT | 41 | 1 | 4 | 103 | 405 | 0.5 |
| Wayne, UT | 6 | 1 | 1 | 30 | 122 | 0.1 |
| Dolores, CO | 4 | 0 | 1 | 10 | 34 | 0.1 |
| Mesa, CO | 118 | 3 | 26 | 33 | 197 | 9.0 |
| Montezuma, CO | 35 | 2 | 5 | 18 | 82 | 0.6 |
| Montrose, CO | 50 | 2 | 7 | 22 | 95 | 1.9 |
| San Miguel, CO | 11 | 1 | 1 | 11 | 45 | 0.1 |

### *Air Pollutant Concentrations*

The concentrations of ozone from 1992-1994 averaged about 50 ppb, with peak 1-hr concentrations of 65-75 ppb (Table 7-3). These concentrations are near the lower end of the range that may produce visible effects or growth effects on very sensitive species (see Chapter 2). However, no reports of injury or growth effects have been noted. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Table 7-3. Concentrations of ozone and $SO_2$ for Bryce Canyon National Park between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the maximum 3-month Sum60 exposure (ppb-hr in excess of 60 ppb, 12 hr/day); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ 24-hr averages from IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1988 | | |
| Mean | | 0.2 |
| Sum60 | | |
| Max | | 0.3 |
| 1989 | | |
| Mean | | 0.2 |
| Sum60 | | |
| Max | | 1.1 |
| 1991 | | |

| | | |
|---|---|---|
| Mean | | 0.3 |
| Sum60 | | |
| Max | | 0.9 |
| 1992 | | |
| Mean | 47 | 0.1 |
| Sum60 | -- | |
| Max | 65 | 0.3 |
| 1993 | | |
| Mean | 47 | 0.2 |
| Sum60 | 4156 | |
| Max | 75 | 1.1 |
| 1994 | | |
| Mean | 51 | 0.2 |
| Sum60 | 16022 | |
| Max | 73 | 0.4 |

### *Visibility*

Visual air quality in Canyonlands National Park has been monitored using a transmissometer, aerosol sampler and a camera at locations near the visitor center at Island in the Sky. The transmissometer began operation in January 1987 and the aerosol sampler began operation in March 1988. The camera operated from July 1982 to April 1995. The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period January 1987 through February 1994. The seasons used are: spring = March, April, and May; summer = June, July, and August; autumn = September, October, and November; and winter = December, January, and February.

### Optical Data - Transmissometer

The transmissometer system consists of two individually-housed primary components: a transmitter (light source) and a receiver (detector). The atmospheric extinction coefficient ($b_{ext}$) at any time can be calculated based on the intensity of light emitted from the source and that measured by the receiver (along with the path length between the two). Transmissometers provide continuous, hourly $b_{ext}$ measurements. Weather factors such as clouds and rain can affect transmissometer measurements, but these can be "filtered out" by removing data points with high relative humidities (RH>90%).

The data are presented by season and annual median values, with and without meteorological factors in Table 7-4 Transmissometer Data Summary. The data are presented in units of extinction coefficient in $Mm^{-1}$ and standard visual range in km. Extinction coefficients represent the ability of the atmosphere to scatter and absorb light. Median values with large differences between the extinction values "including weather" and "excluding weather" indicate periods dominated by precipitation. Higher extinction coefficients signify lower visibility. Similarly, season and annual medians with nearly equal "including weather" and "excluding weather" extinctions indicate visibility reduction caused principally by particles.

Table 7-4. Transmissometer data summary for Canyonlands National Park, January 1987 - November 1994. SVR= standard visual range; $b_{ext}$ = light extinction coefficient.

| Season Year | Excluding Weather | | Including Weather | |
|---|---|---|---|---|
| | SVR (km) | $b_{ext}$ ($Mm^{-1}$) | SVR (km) | $b_{ext}$ ($Mm^{-1}$) |
| Winter 1987 | 125 | 31 | 121 | 32 |
| Spring 1987 | 118 | 33 | 114 | 34 |
| Summer 1987 | 161 | 24 | 161 | 24 |
| Autumn 1987 | 155 | 25 | 149 | 26 |
| Annual 1987 | 138 | 28 | 134 | 29 |
| Winter 1988 | 161 | 24 | 144 | 27 |
| Spring 1988 | 184 | 21 | 176 | 22 |
| Summer 1988 | 176 | 22 | 168 | 23 |
| Autumn 1988 | 161 | 24 | 155 | 25 |
| Annual 1988 | 168 | 23 | 161 | 24 |
| Winter 1989 | 134 | 29 | 129 | 30 |
| Spring 1989 | 155 | 25 | 155 | 25 |
| Summer 1989 | 161 | 24 | 155 | 25 |
| Autumn 1989 | 176 | 22 | 176 | 22 |
| Annual 1989 | 168 | 23 | 161 | 24 |
| Winter 1990 | 193 | 20 | 184 | 21 |
| Spring 1990 | 161 | 24 | 161 | 24 |
| Summer 1990 | 149 | 26 | 149 | 26 |
| Autumn 1990 | 149 | 26 | 149 | 26 |
| Annual 1990 | 155 | 25 | 149 | 26 |
| Winter 1991 | 149 | 26 | 125 | 31 |
| Spring 1991 | 155 | 25 | 155 | 25 |
| Summer 1991 | 155 | 25 | 149 | 26 |
| Autumn 1991 | 161 | 24 | 161 | 24 |
| Annual 1991 | 155 | 25 | 149 | 26 |

| | | | | |
|---|---|---|---|---|
| Winter 1992 | 161 | 24 | 76 | 51 |
| Spring 1992 | 168 | 23 | 161 | 24 |
| Summer 1992 | 161 | 24 | 161 | 24 |
| Autumn 1992 | 134 | 29 | 129 | 30 |
| Annual 1992 | 149 | 26 | 144 | 27 |
| Winter 1993 | 129 | 30 | 105 | 37 |
| Spring 1993 | 144 | 27 | 138 | 28 |
| Winter 1994 | 256 | 15 | 227 | 17 |
| Spring 1994 | 184 | 21 | 184 | 21 |
| Summer 1994 | 161 | 24 | 155 | 25 |
| Autumn 1994 | 184 | 21 | 176 | 22 |
| Annual 1994 | 176 | 22 | 176 | 22 |

No trends were apparent between 1987 and 1994. Visibility tends to be consistently good throughout the year, although high humidity lowers visibility on more days in winter than in other seasons (Table 7-5).

Table 7-5. Standard visual range for Canyonlands National Park. Seasonal averages for median standard visual range in km from January 1987 - November 1994.

| Season | Excluding Weather | Including Weather |
|---|---|---|
| Winter | 163 | 139 |
| Spring | 159 | 156 |
| Summer | 161 | 157 |
| Autumn | 160 | 156 |

## Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 7-6). To compare this table with the data from Table 7-4 and 7-5, the "excluding weather" values should be used. In Table 7-6 the data are presented as seasonal and annual 50th and 90th percentile standard visual range for Canyonlands National Park. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions. The measured extinction data are used to verify the calculated reconstructed extinction and can also be used to run plume and regional haze models and to analyze visibility trends and conditions. Because of the larger spatial and temporal range of the aerosol data, the use of the reconstructed extinction data are preferred.

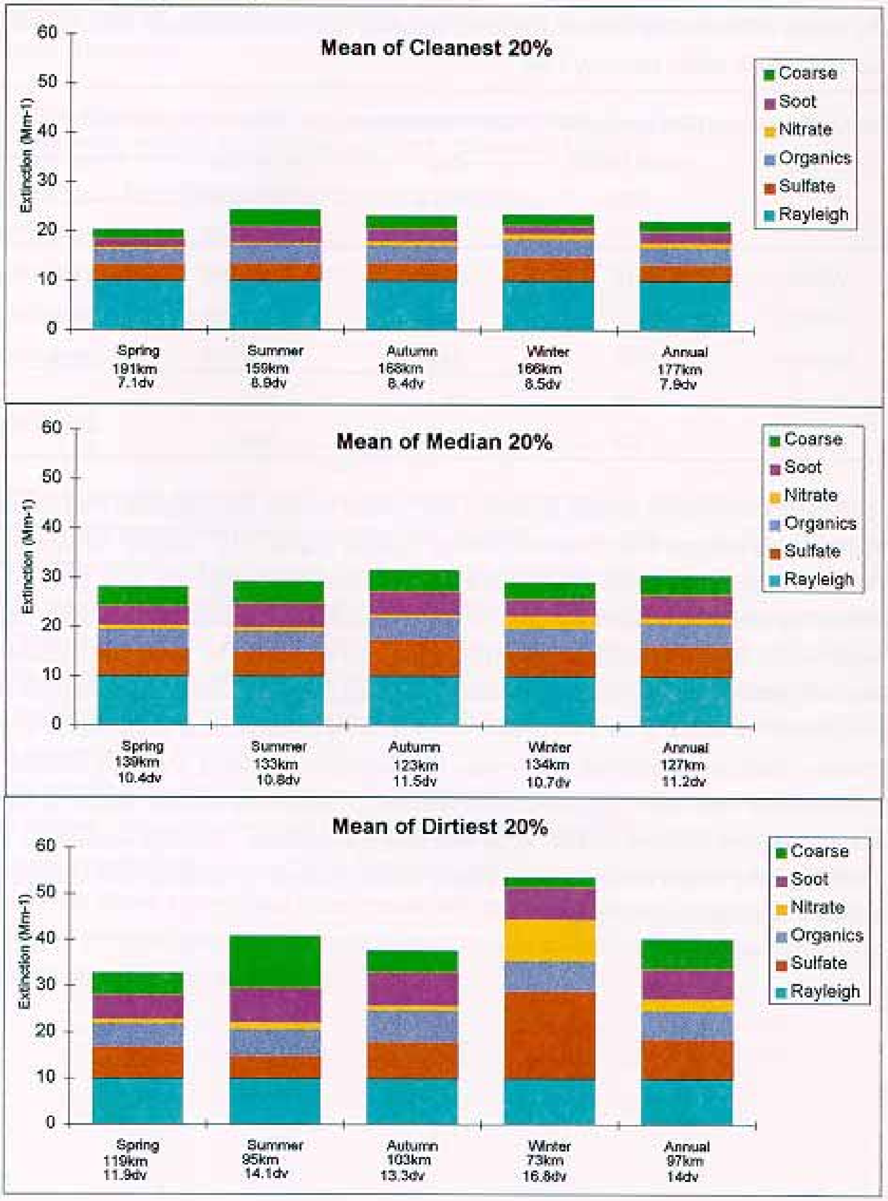
Table 7-6. Reconstructed visual range and light extinction coefficients for Canyonlands National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentiles, March 1988 - February 1994.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 115 | 34.0 | 184 | 21.3 |
| Spring | 143 | 27.3 | 193 | 20.3 |
| Summer | 125 | 31.4 | 154 | 25.3 |
| Autumn | 130 | 30.1 | 182 | 21.4 |
| Annual | 124 | 31.5 | 180 | 21.7 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Canyonlands National Park to specific aerosol species (Figure 7-4). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of the days, mean of median 20% of the days, and mean of dirtiest 20%of the days. The "dirtiest" and "cleanest" signify days with highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicate cleaner conditions.

Figure 7-4. Reconstructed extinction budgets for Canyonlands National Park, March 1993 through February 1994.

**Figure 7-4. Reconstructed extinction budgets for Canyonlands NP, March 1993 through February 1994.**

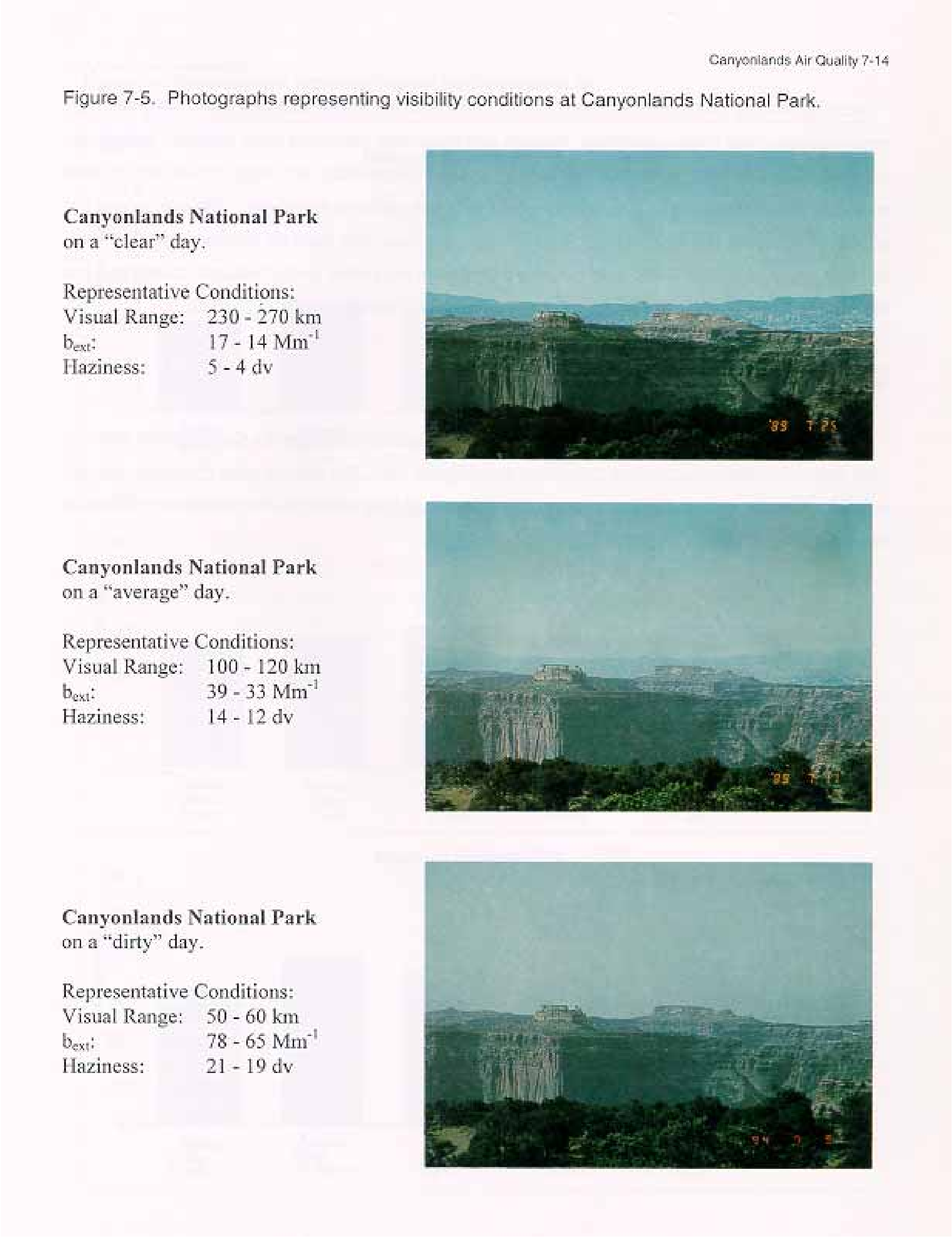


Atmospheric light extinction at Canyonlands National Park is split fairly evenly among sulfates, organics, soot, and coarse particles. Median and clean day visibility is fairly constant throughout the year. The dirtiest days occur in winter, and are associated with high nitrate and sulfate episodes. In pre-industrial times, visibility would vary with patterns in weather, with winds (and the effects of winds on coarse particles), and smoke from fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions, but the cleanest 20% of the days probably approach natural conditions (GCVTC 1996).

## Photographs

Three photos are provided to represent the range of visibility conditions for Canyonlands National Park transmissometer cumulative frequency data (Figure 7-4). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what observers see.

Figure 7-5. Photographs representing visibility conditions at Canyonlands National Park.



Canyonlands Air Quality 7-14

Figure 7-5. Photographs representing visibility conditions at Canyonlands National Park.

**Canyonlands National Park**
on a "clear" day.

Representative Conditions:
Visual Range: 230 - 270 km
$b_{ext}$: 17 - 14 $Mm^{-1}$
Haziness: 5 - 4 dv

**Canyonlands National Park**
on a "average" day.

Representative Conditions:
Visual Range: 100 - 120 km
$b_{ext}$: 39 - 33 $Mm^{-1}$
Haziness: 14 - 12 dv

**Canyonlands National Park**
on a "dirty" day.

Representative Conditions:
Visual Range: 50 - 60 km
$b_{ext}$: 78 - 65 $Mm^{-1}$
Haziness: 21 - 19 dv

## Visibility Projections

The Grand Canyon Visibility Transport Commission (GCVTC 1996) computer modeling analysis projected likely visibility for Canyonlands through 2040, and the major species responsible for visibility impairment (Figures 7-5, 7-6). Reduced emissions from utilities were projected to reduce light extinction by about approximately 1 $Mm^{-1}$. Light extinction caused by vehicle emissions was projected to decline until approximately 2005, and then increase through 2040. There is some concern that the modeling completed by the GCVTC may not adequately represent the relative contribution of near and far away sources, because the modeling analysis did not replicate observed conditions well.

Figure 7-6. Projected “baseline” light extinction for Canyonlands National Park (GCVTC 1996).

Figure 7-6. Projected "baseline" light extinction for Canyonlands National Park (GCVTC 1996).

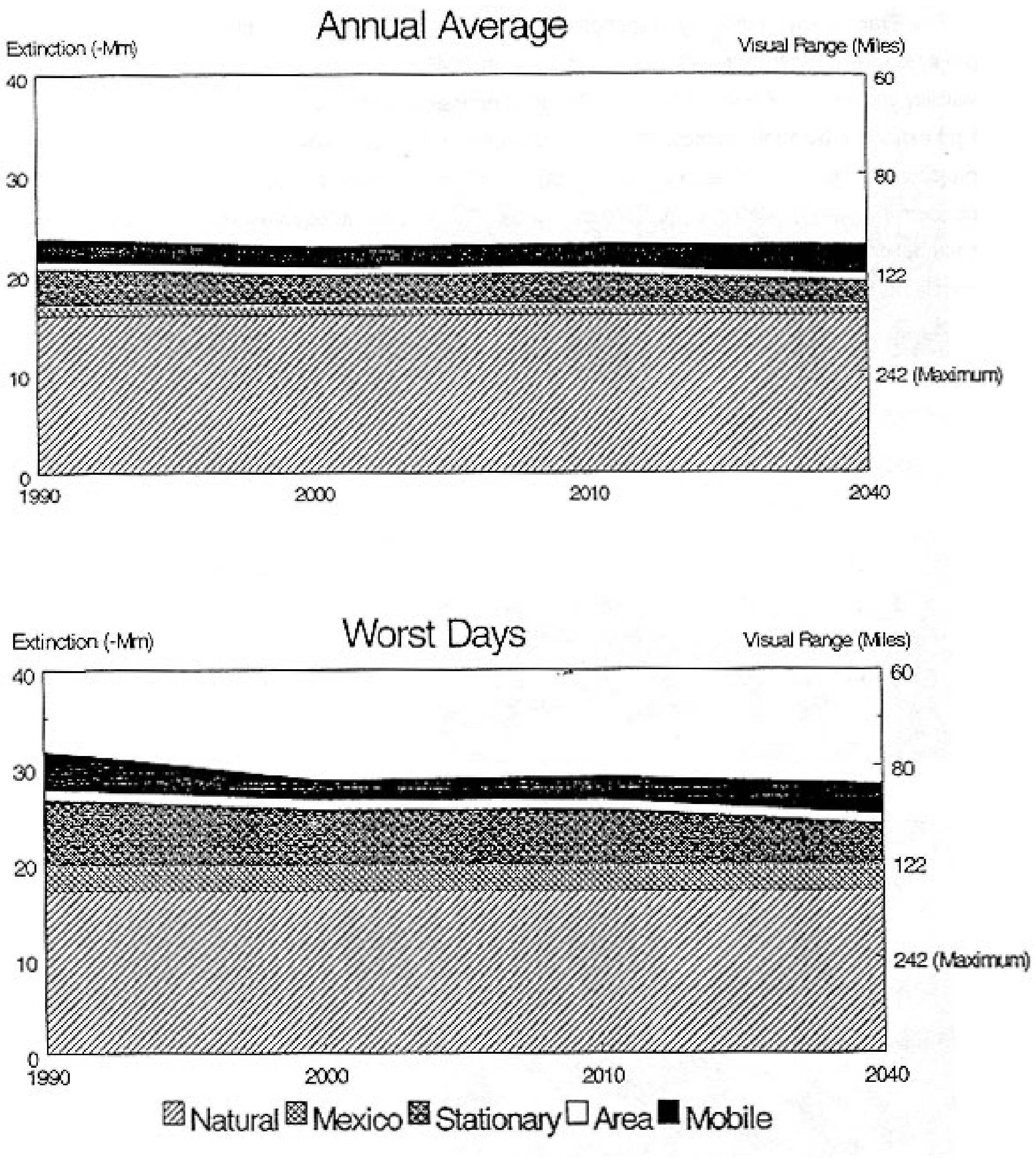


Figure 7-7. Projected “baseline” visibility for Canyonlands National Park for clean, average, and poor visibility periods.

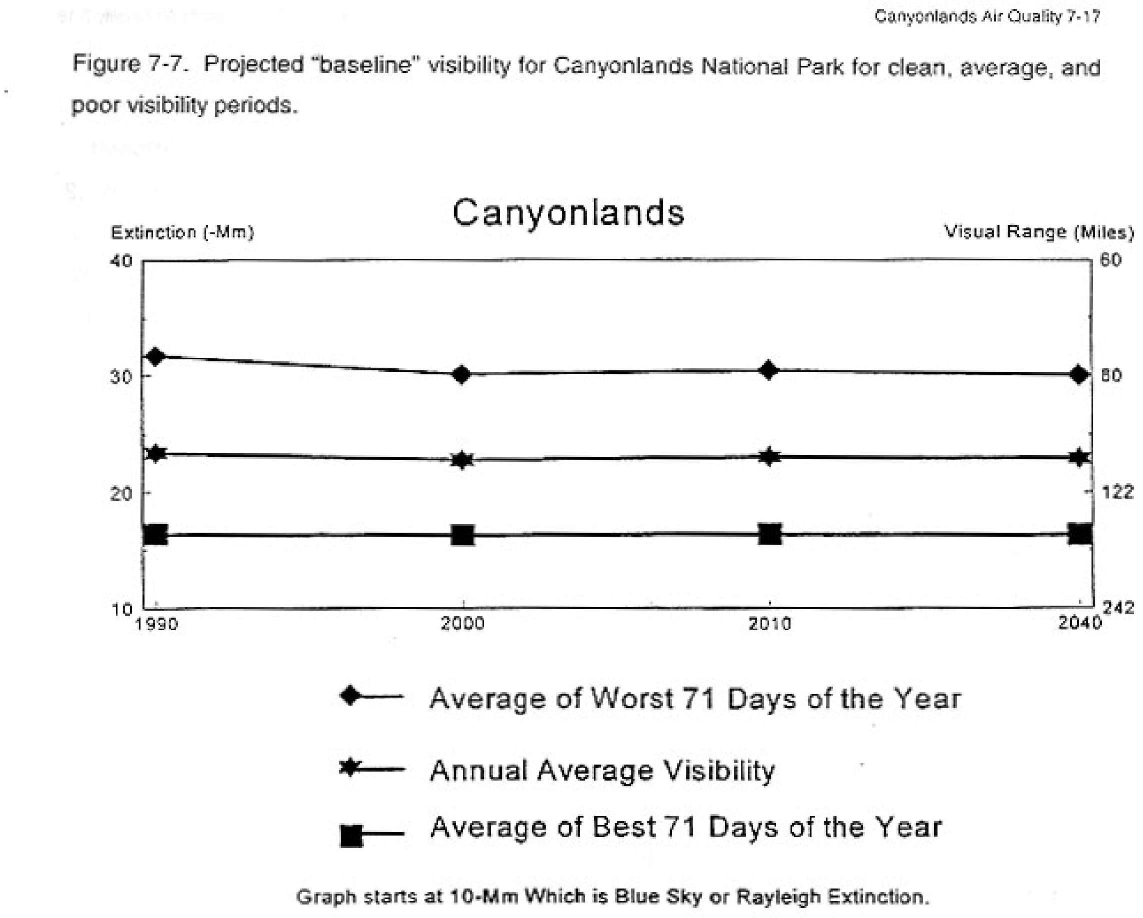


Figure 7-7. Projected “baseline” visibility for Canyonlands National Park for clean, average, and poor visibility periods.

Graph starts at 10-Mm Which is Blue Sky or Rayleigh Extinction.

### *Atmospheric Deposition*

The rates of atmospheric deposition for Green River, Utah (about 70 km northwest of Canyonlands National Park) are relatively low (Table 7-7). Precipitation pH averages about 5.2. Deposition of N averages about 1 kg N $ha^{-1}$ $yr^{-1}$, which is slightly higher than the rate of S deposition. The deposition of both ammonium and nitrate showed significant increasing trends from 1985 through 1994. Ammonium-N deposition increased by about 0.04 kg N $ha^{-1}$ $yr^{-1}$ ($r^2$=0.53, p<0.02) while nitrate-N deposition increased at a rate of 0.03 kg N $ha^{-1}$ $yr^{-1}$ ($r^2$ = 0.44, p<0.04). However, the significance of these trends depends completely on the very low values for the first year of monitoring (1985) when data completeness averaged only 54%. Even if these values were doubled, we suspect the data would be unreliable, being far lower than any other year. We conclude that N deposition probably has not been increasing at Green River. Sulfate deposition showed no trend during this period. There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 7-7. Atmospheric deposition for Green River, Utah (NADP).

| | Concentration (mg/L) | | | Deposition (kg $ha^{-1}$ $yr^{-1}$) | | | | Conductivity | Precipitation |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | (μS/mm) | (mm/yr) |
| 1985 | 0.01 | 0.30 | 0.49 | 0.01 | 0.22 | 0.37 | 5.55 | 0.64 | 75 |
| 1986 | 0.17 | 1.19 | 1.36 | 0.31 | 2.10 | 2.40 | 5.78 | 1.57 | 177 |
| 1987 | 0.48 | 1.27 | 1.40 | 0.86 | 2.26 | 2.49 | 5.35 | 1.18 | 178 |
| 1988 | 0.48 | 1.75 | 1.47 | 0.63 | 2.30 | 1.94 | 5.22 | 1.42 | 132 |
| 1989 | 0.94 | 2.13 | 1.94 | 0.59 | 1.35 | 1.23 | 6.83 | 2.68 | 63 |
| 1990 | 1.00 | 2.04 | 2.17 | 0.66 | 1.35 | 1.43 | 5.82 | 2.40 | 66 |
| 1991 | 0.43 | 1.42 | 1.22 | 0.83 | 2.72 | 2.34 | 5.74 | 1.32 | 192 |
| 1992 | 0.90 | 1.50 | 1.54 | 1.50 | 2.51 | 2.58 | 5.90 | 1.54 | 167 |
| 1993 | 0.53 | 1.33 | 1.33 | 1.10 | 2.77 | 2.77 | 5.58 | 1.14 | 208 |
| 1994 | 0.40 | 1.35 | 1.05 | 0.61 | 2.06 | 1.60 | 5.44 | 1.45 | 150 |

## Sensitivity of Plants

Sanchini (1983) established sampling plots at Canyonlands National Park, tagging some trees and shrubs for long-term monitoring of possible pollutant impacts. She focused on pinyon pine, single-leaf ash, and Utah serviceberry. No symptoms of damage from any air pollutant were observed on these plants nor on any other she examined (including crustose and foliose lichens).

No visible injury signs of air pollution damage have been reported for vegetation in or near Canyonlands National Park. Only a few of the Park's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants, we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

No information is available for water quality or aquatic ecosystems for Canyonlands National Park. Because of the proximity to Arches we would expect that rock pools found in Canyonlands would be similar in chemistry and biological communities to those found in Arches.

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Canyonlands National Park. We recommend that Park staff review bedrock geology maps to determine regions of rock resistant to weathering, and begin to characterize water chemistry and sensitivity to deposition. If rock pools or tinajas occur in these areas of sensitive bedrock, we recommend that water samples be collected in different seasons of the year to determine pH, ANC, and conductance of these waters. If pH values are near 6.0 or less, or ANCs are less than 200 ueq/l, then major anions and cations should be measured. Once sensitivity is determined for selected waters, then a monitoring program can be designed to look for both chronic and episodic changes in chemistry that might be affected by changes in deposition.

## Park Summary

Visibility is currently the only AQRV known to be impacted by pollution at Canyonlands National Park, as with the other Class I NPS areas of the Colorado Plateau. Current levels of pollution in southern Utah are high enough to produce haze and obscure the important vistas of Canyonlands National Park and surrounding areas. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Canyonlands National Park.

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 8. Capitol Reef National Park

## Introduction

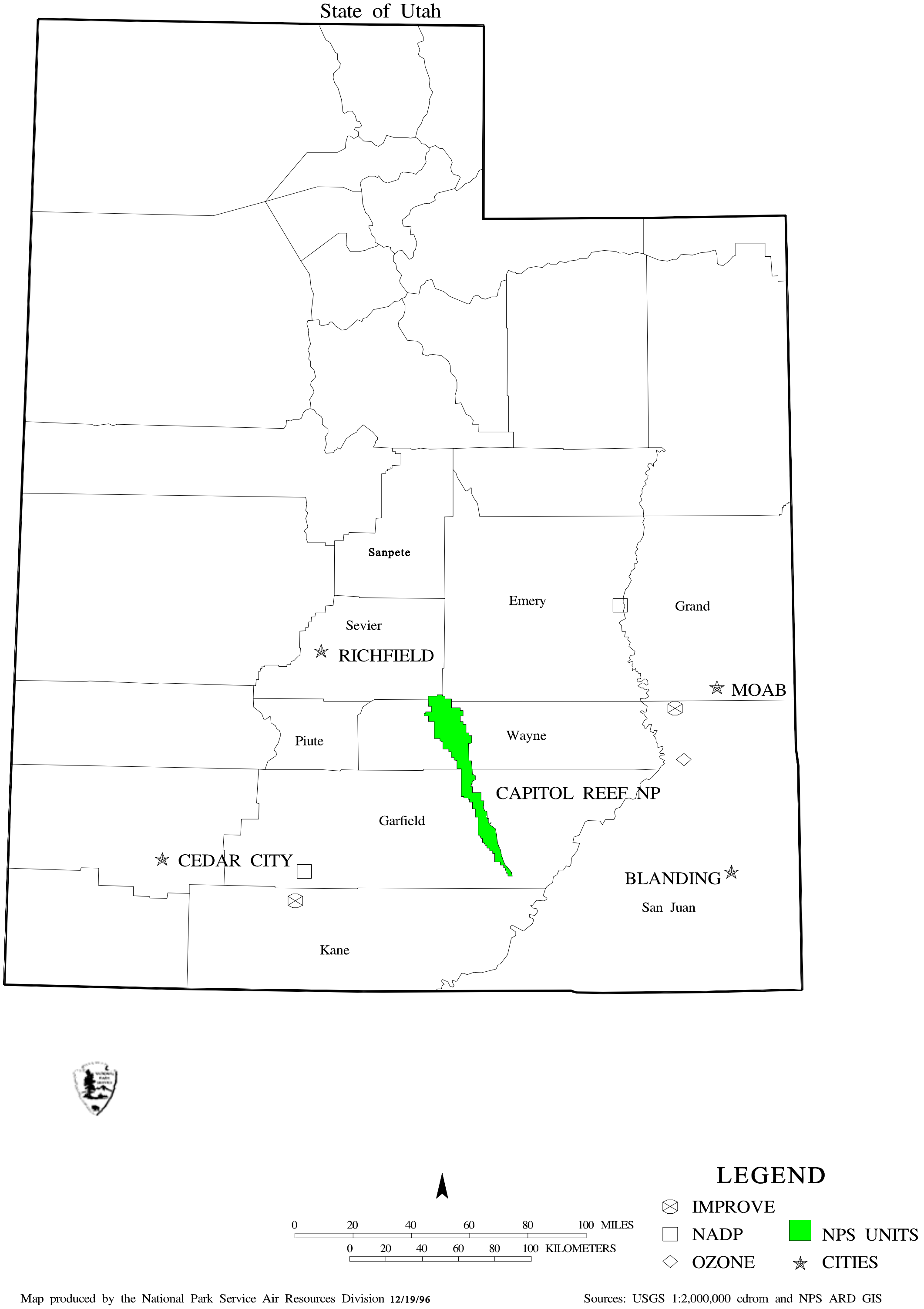
Capitol Reef National Monument was added to the Department of the Interior list of National Monuments in 1937. The monument was expanded to 97,940 ha in 1971 and given National Park status. Today, all but 7100 ha of the 97,940 ha are federally controlled. Capitol Reef National Park is located in south central Utah, and runs north from the Glen Canyon National Recreation Area over 160 km to Cathedral Valley Junction (Figure 8-1). The Park is bordered to the northwest by the Fishlake National Forest, to the southwest by the Dixie National Forest and to the south by the Glen Canyon National Recreation Area. The Park lies in Wayne, Garfield, Sevier and Emery Counties.

The Park was originally established for the remarkable geology of the area. The Waterpocket Fold is a dramatic 160 km monocline, capped primarily by Navajo Sandstone from the Jurassic Period. The extensive folding and erosion has developed a large number of arches and natural bridges, narrow high walled canyons, and large rock domes (from which the name of this park is derived). Archeological sites from the Fremont People are abundant, along with recent historical sites of early Mormon pioneers who settled the region in the late 1800's. Elevation in Capitol Reef National Park ranges from below 1600 m where the Fremont River leaves the Park to 2800 m in the northwest end of the Park near Hartnet Junction. The Park has the best developed and most abundant rock pools of the Colorado Plateau.

### *Geology and Soils*

The oldest sedimentary layers of the Waterpocket Fold were deposited in the Permian Period in a variety of environments. Small outcrops of Cutler Sandstone are the oldest strata visible in the Park, formed during a desert period. Kaibab Limestone layers (the Kaibab formation comprises most of the top layer in the Grand Canyon) sit atop the Cutler, indicating sea encroachment on the ancient desert with no erosional unconformity. The Moenkopi Formation developed in a variable, shallow-sea setting in the Triassic Period, with alternating textures of mudstone, siltstone, and sandstone, mixed with a few limestone strata. The gray and blue Chinle Formation is comprised of mudstone and shale material that weathers into smectite clays with shrink/swell properties (often called bentonite). These “badland” desert systems are sparsely vegetated because plants have difficulty in the easily eroded, shrinking and swelling soils.  The major formations of the Park were

Figure 8-1. Location of Capitol Reef National Park.



Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

deposited after the late Triassic. The Wingate Sandstone formed in a huge desert, which was then replaced by a river floodplain that deposited the Kayenta Siltstone. The Navajo Sandstone was deposited in another desert in the Jurassic Period. Younger formations include the Entrada Sandstone and Cutler Formation, deposited on floodplains and tidal flats, and the youngest Jurassic strata, the Morrison Formation that contains major deposits of dinosaur fossils. A thin layer of Dakota Sandstone deposited in the Cretaceous is topped by massive deposits (1000 m thick) of Mancos Shale. The Mancos Shale weathers into barren, badland soils. The Cenozoic Era has been primarily erosional as a result of the regional uplift (Chronic 1988).

No soils mapping is available for Capitol Reef National Park, but soil formation depends heavily on the parent material. All soils should be relatively high in pH (low in acidity), and very resistant to acidification from acid deposition due to the characteristics of the parent material.

### *Climate*

The climate of Capitol Reef National Park varies with season and elevation. Weather records are scarce for most of the Park; lower elevation sites probably average about 125 mm of precipitation annually, compared with 300 mm at higher elevations. The Park headquarters at Fruita averages about 180 mm/yr, with one third falling in July and August and most of the rest during winter months. Temperature extremes range from -8 $^{o}$C in winter to over 38 $^{o}$C during summer.

### *Vegetation*

Capitol Reef National Park contains six major vegetation communities, and each type can be subdivided into distinct minor communities. The Badlands Community is found on the most severe, low elevation sites in the Park. Substrates tend to be saline and include the clay rich, poor quality soils derived from the Mancos Formation and the gypsiferous soils derived from the Carmel and Moenkopi Formations. Species occurring in this type include saltbush (*Atriplex* spp.), buckwheat (*Eriogonum* spp.), Mormon tea (*Ephedra* spp.), rabbitbrush (*Chrysothamnus* spp.), sagebrush (*Artemisia* spp.) and grasses such as galleta grass (*Pleuraphis jamesii*) and Indian ricegrass (*Achnatherun hymenoides)*.

The Grassland communities are found on deeper sandy soils which are derived primarily from sandstones. They include the grasses *Aristida* spp., *Pleuraphis jamesii*, *Muhlenbergia pungens*, *Bouteloua gracilis*, *Achnatherun hymenoides*, *Stipa comata*, and a variety of forbs, cacti and low shrubs.

The Upland Shrub communities are dominated by blackbrush (*Coleogyne ramosissima*), Mormon Tea (*Ephedra* spp.), sagebrush (*Artemisia* spp.), rabbitbrush (*Chrysothamnus* spp.), greasewood *(Sarcobatus vermiculatus*) and saltbush (*Atriplex* spp.).

The pinyon (*Pinus edulis*) / juniper (*Juniperus osteosperma*) woodlands occupy a range of sites with juniper dominating lower elevation sites and pinyon the higher sites. These communities are often associated with diverse understories of various grasses and shrubs including most of those previously mentioned for the grassland and upland shrub communities.

Upland Forest and Woodland Communities are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with various understories including bitterbrush *(Purshia tridentata*), manzanita (*Arctostaphylos patula*), dogwood (*Cornus stolonifera*), and Rocky Mountain juniper (*Juniperus scopulorum)*. Other tree species include bristlecone pine (*Pinus longaeva*) and aspen (*Populus tremuloides*), both of which form unique restricted higher elevation more mesic communities.

The riparian and wetland communities occur around water sources. Tree species include box elder (*Acer negundo*), Fremont cottonwood (*Populus fremontii*), alder (*Alnus tenuifolia*), river birch (*Betula occidentalis*), and single leaf ash (*Fraxinus anomala*). The understory includes rabbitbrush, saltbush, cacti (*Opuntia* spp.) and grasses such as *Sporolobus contractus*, *Achnatherun hymenoides* and *Muhlenbergia asperifolia*. A detailed listing of plant vegetation in the Park is given by Romme et al. (1993) and Heil et al. (1993) as well as NPFlora. Lichens are abundant as with other parks of the Colorado Plateau and are listed in NPLichen.

Cole (1992) used packrat middens to reconstruct the patterns of vegetation over the past 5400 yrs in Capitol Reef National Park. He concluded that pre-European settlement vegetation was dominated by winterfat (*Eurotia lanata*), Indian ricegrass (*Achnatherun hymenoides*), pinyon pine, and sagebrush. Grazing over the past 100 years produced more severe changes in vegetation than at any other time in the 5000 yr history, shifting to dominance of rabbitbrush, greasewood, and snakeweed. Fisher et al. (1995) used opal phytoliths (small silicaceous granules with characteristic shapes among species) buried in soils to reconstruct vegetation over the past 800 yrs at Capitol Reef National Park. They concluded that ancient communities contained more forbs and shrubs, and that the grass communities were dominated more by cool season (C3) grasses than by warm season (C4) grasses. The period covered by these buried deposits was cooler than present, with likely greater summer moisture that would favor warm-season grasses. Fisher et al. (1995) attribute the shift to warm-season grasses as an indicator of overgrazing because historic grazing used the area in the early season when cool-season grasses were impacted more severely than warm-season grasses that grew primarily after cattle were removed for the season.

The plant species in Capitol Reef listed as endangered are Jones cycladenia (*Cycladenia humilis* var. *jonesii*), Maguire daisy (*Erigeron maguirei* var. *maguirei*), Barneby reed (*Schoencrambe barnebyi*), Wright fishhook cactus (*Sclerocactus wrightiae*), and last chance Townsendia (*Townsendia aprica*) (Heil et al. 1993; Threatened and Endangered Species Information Institute 1993). Species of concern to the NPS include: Ute ladies' tresses (*Spiranthes diluvialis;* Heil et al. 1993), *Gilia caespitosa*, *Pediocactus winkleri, Cymopterus beckii*, *Dalea flavescens* var. *epica*, *Erigeron maguirei* var. *harrisonii*, *Habenaria zothecina*, *Hymenoxys depressa*, and *Thelesperma subnuda* var. *alpina*.

## Air Quality

Air quality monitoring for Capitol Reef National Park consists of ozone concentrations for the summer of 1995 and 1996 (passive collector), and NADP monitoring from Green River, Utah from 1982 to the present. No information is available for sulfur dioxide, particulate concentrations, or visibility. We expect the regional values for this area to resemble Bryce Canyon, Arches, and Canyonlands National Park.

### *Emissions*

Table 8-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 8 counties surrounding Capitol Reef National Park. The largest sources of $SO_x$ in Emery and Carbon Counties in Utah come from three Pacificorp plants (Huntington, Hunter, and Gate). No local information is available to relate these emissions to air quality at Capitol Reef, or to apportion air quality impairment at Capitol Reef National Park to local and regional sources. However, the work by Eatough et al. (1996) to apportion $SO_x$ sources for Canyonlands National Park and Green River, Utah probably relate to Capitol Reef. Eatough et al. (1996) apportioned the $SO_x$ in Canyonlands to emission sources over a 3-month period from January through March in 1990, based on "fingerprints" of ratios of compounds in the air, and air mass trajectories. For example, emissions from 2 coal-fired power plants had high ratios of spherical aluminosilicate particles to sulfate, but very low ratios of arsenic to sulfate. Air from Arizona was characterized by low ratios of these aluminosilicate particles to sulfate, and high ratios of arsenic to sulfate. They concluded that $SO_x$ in Canyonlands National Park derived from a wide range of regional sources rather than from a dominant source; about 37% (during a 21 day period) came from the southwest, 20% from the south/southeast, 19% from the north/northeast, and 23% from the northwest. Eatough et al. (1996) concluded that the major sources of $SO_2$ were from the southwest, while major sources of particulate sulfate were from the southeast. To the northwest at Green River, Utah Eatough et al. (1996) found that a larger portion of the $SO_x$ came from the southeast, and substantially less from the Utah Power and Light (now Pacificorp) generating stations to the North in the Green River Basin.

Table 8-1. Emissions (tons/day) for counties surrounding Capitol Reef National Park (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Emery, UT | 40.49 | 0.70 | 114 | 56 | 273 | 51.73 |
| Garfield, UT | 13.69 | 0.60 | 1.46 | 63 | 253 | 0.22 |
| Kale, UT | 14.88 | 0.26 | 1.59 | 44 | 114 | 0.21 |
| Piute, UT | 4.59 | 0.35 | 0.51 | 9 | 8 | 0.06 |
| San Juan, UT | 40.75 | 0.66 | 3.87 | 103 | 405 | 0.45 |
| Sanpete, UT | 41.63 | 1.81 | 5.34 | 20 | 72 | 1.13 |
| Sevier, UT | 36.47 | 1.06 | 4.79 | 24 | 58 | 1.25 |
| Wayne, UT | 6.34 | 0.62 | 0.74 | 30 | 122 | 0.11 |

### *Air Pollutant Concentrations*

Ozone concentrations in the summer of 1995 averaged 41 ppb on a weekly basis, with a peak weekly average of 46 ppb. These concentrations fall at the bottom end of the range that may produce visible effects or growth effects on very sensitive species (see Chapter 2), but no reports of injury or growth effects have been noted. No information is available for $SO_2$, but the low values for the entire region indicate that levels at Capitol Reef National Park should be far below any threshold of plant sensitivity.

*Atmospheric Deposition*

The rates of atmospheric deposition for Green River, Utah (about 100 km northeast of Capitol Reef) are relatively low (Table 8-2). Precipitation pH averages about 5.2. Deposition of N averages about 1 kg N ha$^{-1}$ yr$^{-1}$, which is slightly higher than the rate of S deposition. The deposition of both ammonium and nitrate showed significant increasing trends from 1985 through 1994. Ammonium-N deposition increased by about 0.04 kg N ha$^{-1}$ yr$^{-1}$ ($r^2$=0.53, $p<0.02$) while nitrate-N deposition increased at a rate of 0.03 kg N ha$^{-1}$ yr$^{-1}$ ($r^2 = 0.44$, $p<0.04$). However, the significance of these trends depends completely on the very low values for the first year of monitoring (1985) when data completeness averaged only 54%. Even if these values were doubled, we suspect the data would be unreliable, being far lower than any other year. We conclude that N deposition probably has not been increasing at Green River. Sulfate deposition showed no trend during this period. There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 8-2. Atmospheric deposition for Green River, Utah (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentration (mg/L) | | | Deposition (kg ha$^{-1}$ yr$^{-1}$) | | | | Conductivity | Precipitation |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | (µS/mm) | (mm/yr) |
| 1985 | 0.01 | 0.30 | 0.49 | 0.01 | 0.22 | 0.37 | 5.55 | 0.64 | 75 |
| 1986 | 0.17 | 1.19 | 1.36 | 0.31 | 2.10 | 2.40 | 5.78 | 1.57 | 177 |
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| 1988 | 0.48 | 1.75 | 1.47 | 0.63 | 2.30 | 1.94 | 5.22 | 1.42 | 132 |
| 1989 | 0.94 | 2.13 | 1.94 | 0.59 | 1.35 | 1.23 | 6.83 | 2.68 | 63 |
| 1990 | 1.00 | 2.04 | 2.17 | 0.66 | 1.35 | 1.43 | 5.82 | 2.40 | 66 |
| 1991 | 0.43 | 1.42 | 1.22 | 0.83 | 2.72 | 2.34 | 5.74 | 1.32 | 192 |
| 1992 | 0.90 | 1.50 | 1.54 | 1.50 | 2.51 | 2.58 | 5.90 | 1.54 | 167 |
| 1993 | 0.53 | 1.33 | 1.33 | 1.10 | 2.77 | 2.77 | 5.58 | 1.14 | 208 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1994 | 0.40 | 1.35 | 1.05 | 0.61 | 2.06 | 1.60 | 5.44 | 1.45 | 150 |

## Sensitivity of Plants

No signs of air pollution injury have been reported for vegetation in or near Capitol Reef National Park. Only a few of the Park's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants, we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

Water resources in Capitol Reef include the Fremont River, perennial, intermittent, and ephemeral streams and numerous springs. Water quality data from EPA's national data bases were retrieved for sampling sites in the park (NPS 1994). In general the pH range for permanent waters in Capitol Reef was 6.5 to 9.0; the highest values came from the Fremont River.

Lafrancois (1995, 1996) examined pools sitting on bedrock and in wetlands from 1993 to 1994. These are a subset of the more than 460 rock pools found along the Waterpocket Fold, most of which occur on sandstone outcrops. The rock pool biological communities included 53 species of macroinvertebrates and anurans. Two insect species, *Notonecta kirbyi* and *Rhantus gutticolis*, were significantly more abundant in wetland pools. The biggest determinants of species abundances in these rock pools were physical factors: flooding of the pools and evaporation of the pools as the summer season progressed.

The chemistry of rock pools in Capitol Reef was studied at three locations in the Park: Cottonwood Tanks, Muley Tanks and Fountain Tanks (located from north to south in the park). The range of pH in these tanks was 7.0 to 7.6, with very high ANC ranging from about 500 μeq/L to about 1230 μeq/L (Table 8.3). Compared to the two more northern sites, the Fountain Tanks rock pools had significantly higher concentrations of ANC, silica, conductivity, sulfate, and base cations.

This appears to be the result of differences in bedrock minerology. The relatively high pH and ANC values for these rock pools indicate high resistance to acidification; the sandstone substrate for these pools is more able to buffer acidic inputs. There is no information on whether deposition of N in major storms could affect these pools, especially in relation to allochthonous inputs of organic material.

Table 8-3. Water chemistry from tanks in Capitol Reef National Park (J. Baron, unpublished data).

| Parameter | Cottonwood Tanks | Muley Tanks | Fountain Tanks |
|---|---|---|---|
| pH | 7.0 | 7.3 | 7.6 |
| Conductivity µS/cm | 53 | 62 | 115 |
| Calcium, mg/L | 7.7 | 8.7 | 21.0 |
| Magnesium, mg/L | 1.4 | 1.6 | 3.3 |
| Sodium, mg/L | 0.4 | 0.4 | 0.8 |
| Potassium, mg/L | 1.3 | 1.7 | 1.1 |
| Ammonium-N, mg/L | 0.3 | 0.4 | 0.1 |
| Chloride, mg/L | 0.6 | 0.7 | 1.1 |
| Nitrate-N, mg/L | 0.1 | 0.1 | 0.1 |
| Sulfate-S, mg/L | 0.7 | 0.4 | 1.2 |
| Phosphate-P, mg/L | 0.0 | 0.0 | 0.0 |
| ANC, µeq/L | 503 | 555 | 1227 |
| Silica, mg/L | 0.8 | 0.5 | 1.4 |

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Capitol Reef National Park. Air quality is not monitored at Capitol Reef National Park, although information from Canyonlands NP, Bryce Canyon NP and other sites provides an approximate picture of air quality at Capitol Reef NP. Installation of a full IMPROVE site would not be warranted, but we recommend smaller scale, on-site monitoring of visibility and ozone.

The pothole aquatic ecosystems in the Park appear to be very well buffered with respect to acidification, and we have no recommendations for further research on acidity features; some monitoring may be useful. We do not know enough about the biogeochemistry of these systems and their watersheds to conclude that deposition of N and S species will not change both the chemistry and the biota of these unique systems. If funds are available, we recommend that time series data on chemistry of selected system be collected, with emphasis on the period following intense rain storms that could flush accumulated dry deposition into the pools. Chemical parameters to be monitored include: pH, ANC, ammonium, nitrate and sulfate. Analysis for sulfur isotopes could provide information on the source of the sulfate in pools (e.g. power plants, smelters). Manipulation experiments could be conducted on adjacent lands in similar types of aquatic systems. These experiments could include the additional of S and N compounds to either the rock pools or the watersheds of these pools to measure changes in surface water chemistry and biota.

## Park Summary

Without substantial monitoring information, the status of AQRVs at Capitol Reef can only be inferred from the general picture across the Plateau. Visibility is currently the only AQRV known to be impacted by pollution in other Class I NPS areas of the Colorado Plateau. Current levels of pollution in southern Utah are probably high enough to produce haze and obscure the important vistas of the Park and surrounding areas. Any increase in aerosols would undoubtedly impair visibility further; substantial reductions in aerosols would probably be needed to restore pristine conditions at Capitol Reef National Park.

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 9. Grand Canyon National Park

## Introduction

The Grand Canyon was established as a forest reserve in 1893, and later became the Grand Canyon Game Preserve in 1906, the Grand Canyon National Monument in 1908, and finally the Grand Canyon National Park in 1919. A separate Grand Canyon National Monument was established west (downriver) of the Park in 1932, and Marble Canyon National Monument was created in 1969 to the northeast (upriver). The National Park reached its present size of over 492,800 ha when Grand Canyon and Marble Canyon National Monuments were added along with additional area around Toroweap and upper Lake Mead (Figure 9-1). In 1979, Grand Canyon National Park was designated a World Heritage Site because of the tremendous natural and geologic value contained in the Park.

Grand Canyon National Park is in northern Arizona, with park headquarters about 100 km north of Flagstaff. Over 400 km of the Colorado River are included in the Park. Neighboring lands include the Kaibab National Forest, Glen Canyon and Lake Mead National Recreation Areas, the Arizona Strip District of the BLM, and reservations belonging to the Navajo, Hualapai, and Havasupai tribes.

The exposed geology of the canyon spans 2 billion years and a maximum drop in elevation of about 1860 m. The region of the Grand Canyon National Park includes seven plateaus, including the Kanab, Kaibab, and Coconino and the low lying Marble Platform that are separated by many faults and monoclines. Elevations for the Grand Canyon National Park range from 353 m at Lake Mead to almost 2800 m on the North Rim. Because of the dramatic topography and huge elevational changes, climate is extremely variable in temperature and moisture. The Park contains an abundance of archeological sites.

### *Geology and Soils*

The oldest formation in the Grand Canyon National Park is the Vishnu Schist (Chronic 1988), which comprises the Inner Gorge. The Vishnu, Brahma and Rama Schists are the highly metamorphosed sediments eroded from mountains more than 2 billion years ago off the “coast” of North America. The schist has major intrusions of pink Zoroaster Granite (from about 1.75 million years ago). The rocks were later “welded” onto the North American tectonic plate (Bradley et al.

1996). In the late Precambrian (1250-825 million years ago) over 3 km of sediments and lava were deposited (forming the Grand Canyon Supergroup, Elston 1989). Later uplift, tilting, and erosion removed most of this material. Only a few tilted, wedge-shaped layers remain in the eastern end of the Park, beneath the "Great Unconformity." From 500 to 245 million years ago, coastal environments dominated the Grand Canyon area as gradual sinking allowed deposition of sedimentary layers. Early Paleozoic marine deposits include the beach sands of Tapeats Sandstone and off-shore deposits of limestones (Muav, Temple Butte, Redwall).

Mountain building to the east of the Grand Canyon in the later Paleozoic provided sedimentary materials for the Supai Group, Herman Shale, and Coconino Sandstone. Occasional marine advances provided material for Pakoon, Toroweap, and Kaibab Limestones.

In the Mesozoic era, about 1500 m of additional strata were deposited in the Grand Canyon area, but subsequent uplift led to massive erosion of these strata that can still be seen in other regions of the Colorado Plateau.

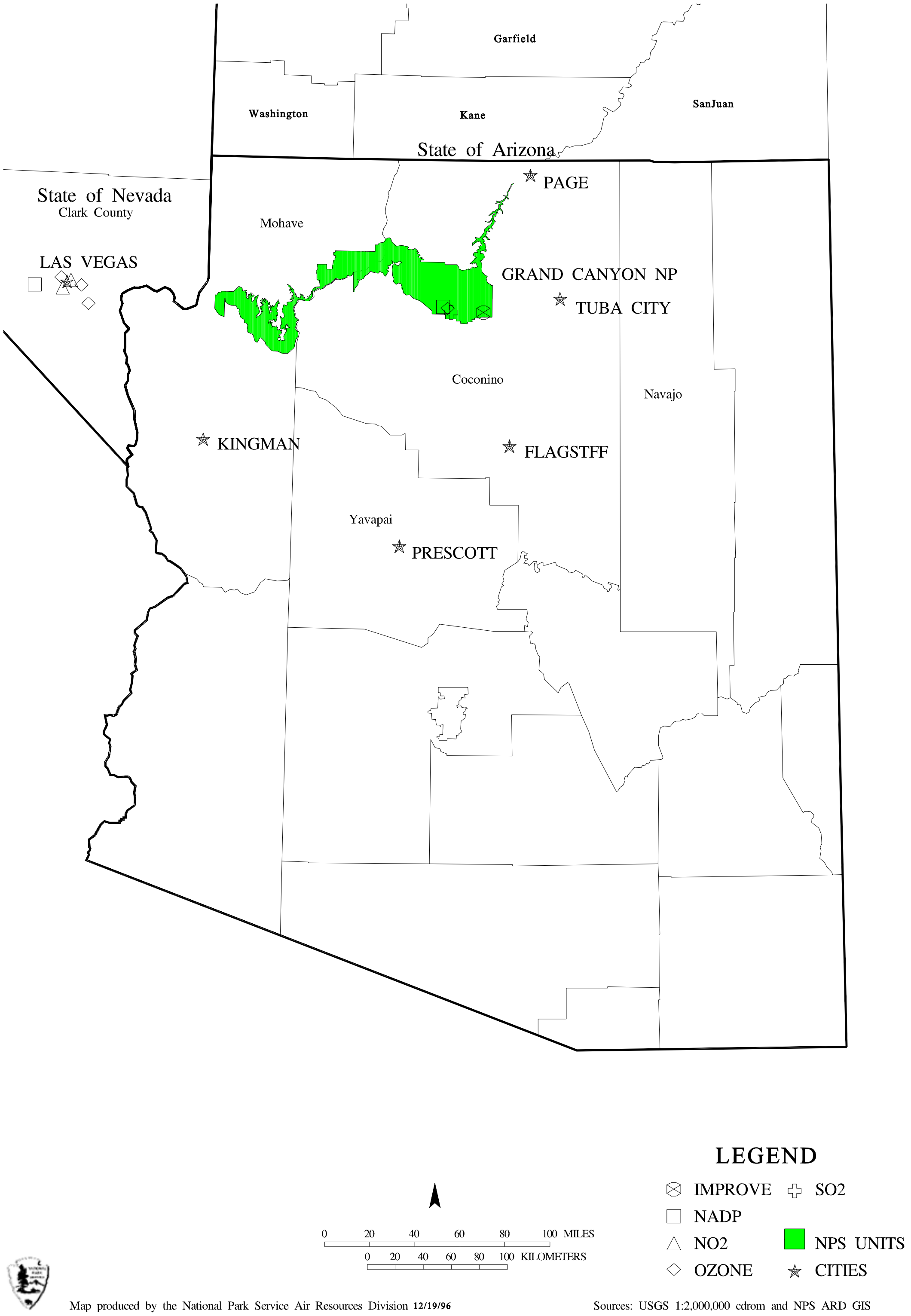
The carving of the Grand Canyon probably occurred over a period of 6 million years, with the Canyon reaching its current depth about 1 million years ago based on dating of exposed volcanic flows in the bottom of the Canyon.

The soils of the Grand Canyon National Park strongly reflect the parent materials and dry climate, and none should be sensitive to acidification from acid deposition.

### *Climate*

The tremendous elevational gradient in the Grand Canyon results in huge variation in temperatures and moisture with corresponding changes in vegetation. The mean monthly temperature for January and July at the South Rim are -2 $^{o}$C and 19 $^{o}$C, with an average total precipitation of 500 mm/yr (Figure 9-2). Temperatures at the bottom of the Canyon average about 3-5 $^{o}$C warmer, and precipitation declines by about half down to the river. The winds at the South Rim come predominantly from the southwest, except for late autumn when substantial winds also come from the northeast (Figure 9-3).

Figure 9-1. Location of Grand Canyon National Park.



Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

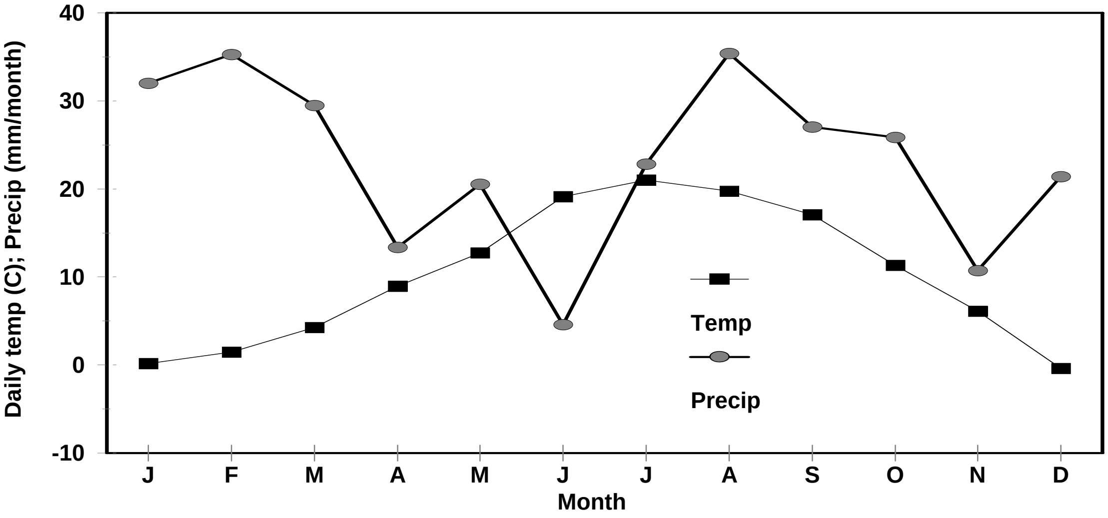
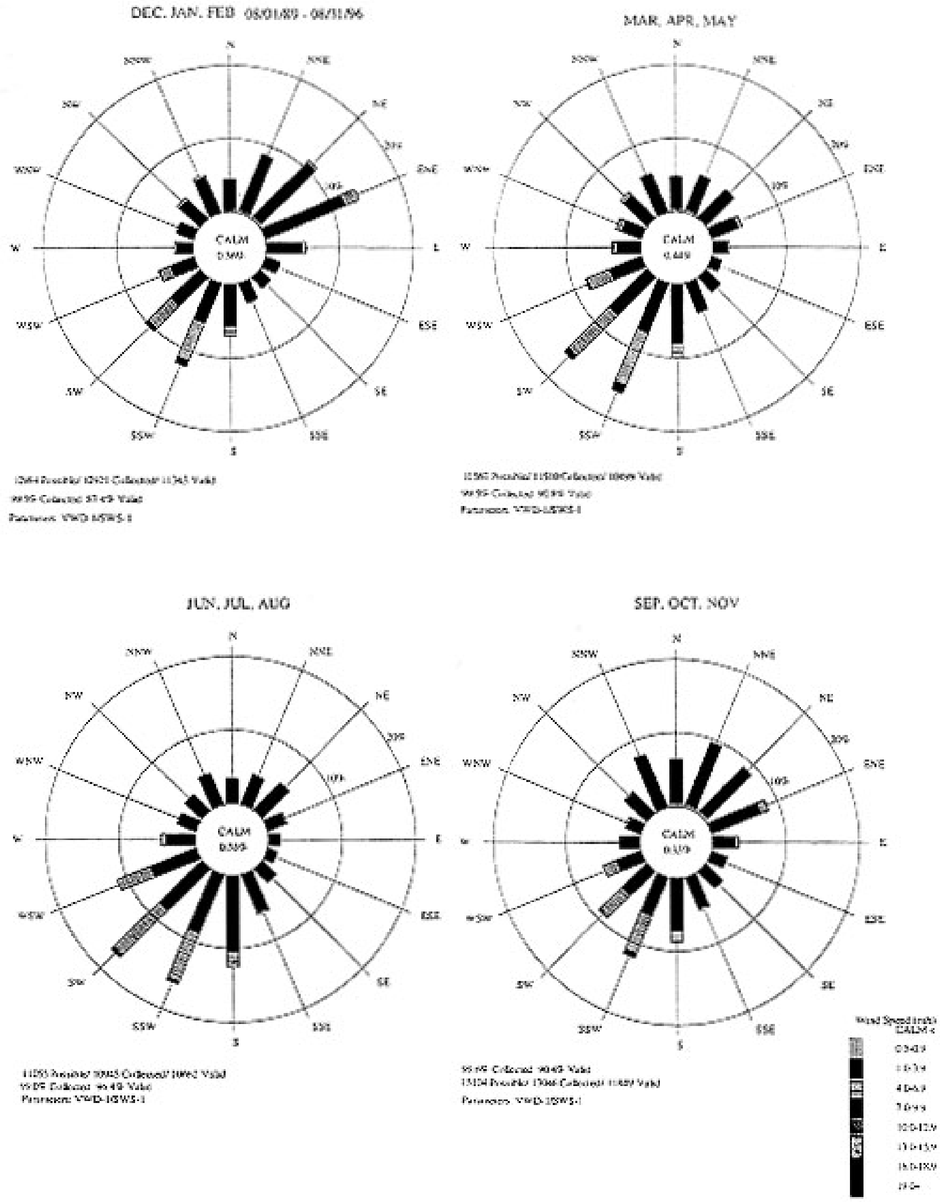

Daily temp (C); Precip (mm/month)
40
30
20
10
0
-10
J
F
M
A
M
J
J
A
S
O
N
D
Month
Temp
Precip

Figure 9-3. Seasonal wind roses for Grand Canyon National Park for 1989-1996.

Grand Canyon Air Quality 9-5

Figure 9-3. Seasonal wind roses for Grand Canyon National Park for 1989-1996.



### *Vegetation*

Grand Canyon National Park has a wide variety of vegetation communities, from very arid communities characteristic of deserts of southern Arizona and California to conifer forests characteristic of the Rocky Mountains (Table 9-1). The communities along the river and lower reaches of tributary canyons include Fremont cottonwood (*Populus fremontii*), mesquite (*Prosopis juliflora*), acacia (*Acacia greggii*), and a variety of native willow species including coyote willow (*Salix exigua*) and Goodding willow (*Salix gooddingii*). Most low-elevation riparian zones have major infestations of exotic tamarisk (*Tamarix ramosissima*). At lower elevations (typically below the Redwall) away from water sources, Mojave and Sonoran Desert scrub communities dominate, with blackbrush (*Coleogyne ramosissima*), saltbush (*Atriplex canescens*) creosote bush *(Larrea tridentata*), Mormon tea (*Ephedra* spp.), snakeweed (*Gutierrezia sarothrae*) and various cactus species. The mid-elevation vegetation is typically dominated by the pinyon (*Pinus edulis*) / juniper (*Juniperus osteosperma*, *J. monosperma*) community from the top of the Redwall into the Coconino sandstone. Ponderosa pine (*Pinus ponderosa*) communities mixed with Gambel oak (*Quercus gambelii*) cover extensive areas of the South Rim and lower elevations of the North Rim. Communities of spruce (*Picea engelmannii*) and white fir (*Abies concolor*) on the North Rim include aspen (*Populus tremuloides*) and Douglas-fir (*Pseudotsuga menzeisii*). Riparian communities in the Grand Canyon National Park include mesic plant communities with Fremont cottonwood (*Populus fremontii*), single leaf ash (*Fraxinus anomala*), hoptree (*Ptelea trifoliata*), hophornbeam (*Ostrya knowltonii*), serviceberry (*Amelanchier utahensis*), redbud (*Cercis occidentalis*), Apache plume (*Fallugia paradoxa*), squawbush (*Rhus trilobata*) and many others. The Grand Canyon National Park has only one plant species listed as endangered: the Sentry milkvetch (*Astragalus cremnophylax* var. *cremnophylax*) (Threatened and Endangered Species Information Institute 1993). Species of special concern for the NPS include: bear paw poppy (*Arctomecon californica*), Roaring Springs prickle poppy (*Argemone arizonica*), bunchflower evening primrose (*Camissonia confertifolia*), cave dweller primrose (*Camissonia specuicola* ssp. *hesperia*), Grand Canyon rose (*Rosa stellata* ssp. *abyssa*), Grand Canyon catchfly (*Silene rectiramea*), and Tusayan flame flower (*Talinum validulum*). None of these plants are suspected of being threatened by air quality. A full listing of plant species in the Park is provided in NPFlora, and lichen species are listed in NPLichen.

Table 9-1. Vegetation communities which comprise > 0.1% of Grand Canyon National Park (provided by NPS staff, Grand Canyon National Park).

| Community type | % of Park |
|---|---|
| Snakeweed-Mormon Tea-Utah Agave | 10.8 |
| Blackbrush-Mormon Tea-Banana Yucca | 9.4 |
| Juniper-Pinyon-Mormon Tea-Scrub Oak | 6.8 |
| Juniper-Big Sagebrush-Pinyon | 5.7 |
| Mormon Tea-Snakeweed-Wolfberry | 5.4 |
| Pinyon-Scrub Oak-Manzanita | 5.1 |
| Brittlebush-Creosotebush-Mormon Tea | 5.0 |
| Scrub Oak-Snakeweed-Beargrass-Blackbush | 4.7 |
| Blackbrush-Pinyon-Juniper | 4.4 |
| Desert Mallow-Mormon Tea-Creosotebush | 3.5 |
| Brittlebush-Mormon Tea-Catclaw Acacia | 3.1 |
| Juniper-Pinyon-Mormon Tea-Greasebush | 2.9 |
| Mormon Tea-Blackbrush-Creosotebush | 2.8 |
| Big Sagebrush-Snakeweed-Mormon Tea | 2.6 |
| Ponderosa-White Fir-Aspen | 2.3 |
| Pinyon-Serviceberry-Gambel Oak | 2.2 |
| Ponderosa-Pinyon-Gambel Oak-Juniper | 1.8 |
| Pinyon-Juniper-Big Sage-Cliffrose | 1.7 |
| Pinyon-Juniper-Scrub Oak-Little Leaf Mtn Mahogany | 1.5 |
| Big Sagebrush-Juniper-Pinyon | 1.5 |
| Big Sagebrush-Snakeweed-Blue Gramma | 1.5 |
| Sandpaper bush-Pinyon-Snakeweed | 1.3 |
| Engelmann Spruce-White Fir-Ponderosa | 1.3 |
| Ponderosa-Aspen-White Fir-Douglas Fir | 1.3 |
| Ponderosa Pine | 1.1 |
| Juniper-Pinyon-Big Sagebrush | 0.9 |
| Ponderosa-NMex Locust-Gambel Oak | 0.7 |
| Creosotebush-White Bursage-Mormon Tea | 0.7 |
| Mormon Tea-Big Galleta-Catclaw Acacia | 0.7 |
| Saltbush-Banana Yucca-Snakeweed | 0.6 |
| Pinyon-Juniper-bluegrass | 0.6 |
| Desert Mallow-Indigo bush-Ocotillo | 0.6 |
| Creosotebush-Beavertail Cactus-Ocotillo | 0.5 |
| Shadscale-Mormon Tea-Beavertail Cactus | 0.5 |
| Blackbrush-Banana Yucca-Cliffrose | 0.5 |
| Engelmann Spruce-Subalpine Fir | 0.5 |
| Mixed Grass-forb Association | 0.4 |
| Ponderosa-Gambel Oak-White Fir-NMex Locust | 0.4 |
| White Bursage-Mormon Tea-Barrel Cactus | 0.3 |
| Douglas Fir-White Fir-NMex Locust | 0.3 |
| Black Sagebrush-Saltbush-Mormon Tea | 0.2 |
| Big Sagebrush-Saltbush-Mormon Tea | 0.2 |
| Hilaria-Cheatgrass-Snakeweed | 0.2 |
| Catclaw Acacia-Baccharis-Apache Plume | 0.2 |
| Ponderosa-Aspen-Engelmann Spruce | 0.2 |
| Fourwing Saltbush-Winterfat-Mormon Tea | 0.2 |
| Rabbitbrush-Snakeweed-Fourwing Saltbush | 0.2 |
| Ponderosa-Gambel Oak-Big Sagebrush | 0.1 |
| Blackbrush-Joshua Tree-Banana Yucca | 0.1 |
| Cottonwood-Brickellia-Acacia-Apache Plume | 0.1 |

| | |
|---|---|
| Aspen-Ponderosa-Engelmann Spruce | 0.1 |
| Fourwing Saltbush-Big Sagebrush-Snakeweed | 0.1 |
| Ponderosa-Pinyon-Cliffrose-Black Sagebrush | 0.1 |

## Air Quality

Air quality monitoring for the Grand Canyon consists of ozone monitoring (1983, 1989-present, and 1995/1996 as part of the EPA CASTNet program), NADP monitoring from 1981 to the present, NDDN estimates of dry deposition for 1990-1991, $SO_2$ measurements from 1988-present (omitting 1990), and IMPROVE monitoring for visibility from 1988 to the present. Three photographs/day are taken for visibility at Desert View. A nephelometer is planned for installation at Grandview Point. Air quality issues at the Grand Canyon National Park and other Class I areas of the Colorado Plateau were the focus of the GCVTC (1996) which was mandated in the 1990 Clean Air Act Amendments. A USDA ultraviolet radiation monitoring station was set up in 1996, and the State of Arizona has monitored airborne particulate radiation at two sampling sites on the South rim since 1994 (Arizona Radiation Regulatory Agency 1994).

### *Emissions*

Table 9-2 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 8 counties surrounding the Grand Canyon National Park. These local emissions are relatively low, with the exception of Coconino County's Navajo Generating Station of the Salt River Project. A micro-inventory of emissions was developed for 1993 for the Grand Canyon (Radian 1994b; C. Bowman, personal communication). The micro-inventory found that mobile sources (vehicles on roads, boats, and aircraft) were the predominant sources of visibility-reducing pollutants (Table 9-3), with prescribed fires contributing less than half of the local emissions. The Park did not add appreciably to the total emissions of Coconino County, although local emissions are higher than those typically used to represent "rural" areas. The GCVTC (1996) concluded that emissions from source areas of pollution for Grand Canyon National Park should decline by about 30% from the 1990 levels by sometime between 2000 and 2010, as a result of improved emission control for point sources and declining emissions from the copper smelting industry.

Table 9-2. Emissions (tons/day) for counties surrounding Grand Canyon National Park (Radian 1994a).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_X$ |
|---|---|---|---|---|---|---|
| Garfield, UT | 13.69 | 0.60 | 1.5 | 63 | 253 | 0.2 |
| Kane, UT | 14.88 | 0.26 | 1.6 | 44 | 114 | 0.2 |
| San Juan, UT | 40.75 | 0.66 | 3.9 | 103 | 405 | 0.5 |
| Washington, UT | 63.71 | 0.55 | 6.5 | 34 | 189 | 0.9 |
| Coconino, AZ | 145.54 | 3.17 | 132.8 | 209 | 659 | 213.2 |
| Mohave, AZ | 99.74 | 1.16 | 22.0 | 224 | 784 | 1.5 |
| Navajo, AZ | 167.34 | 2.74 | 78.8 | 83 | 559 | 67.7 |
| Yavapai, AZ | 144.08 | 2.71 | 27.1 | 114 | 653 | 2.6 |
| Clark, NV | 580.40 | 1.64 | 187.2 | 117 | 606 | 128.0 |

Table 9-3. Micro-inventory of emissions in Grand Canyon National Park in 1993 (Radian 1994b, C. Bowman, personal communication). Wildfires and prescribed fires not included.

| Source category | $SO_2$ | $NO_x$ | Particulate Matter | Volatile Organic Compounds |
|---|---|---|---|---|
| Commercial/Institutional fuel combustion | 14.0 | 12.0 | 0.7 | 0.7 |
| Residential fuel combustion (LPG) |  | 0.1 |  |  |
| Residential wood combustion | 0.1 | 0.7 | 7.8 | 6.5 |
| Highway vehicles - gasoline | 6.2 | 150.0 | 2.3 | 160.0 |
| Highway vehicles - diesel | 28.0 | 170.0 | 16.0 | 39.0 |
| Aircraft | 6.5 | 84.0 | 17.0 | 69.0 |
| Recreational boating - gasoline | 2.9 | 8.6 | 47.0 | 870.0 |
| Trains - diesel | 1.4 | 2.5 | 0.1 | 0.1 |
| Road dust from paved roads |  |  | 1950.0 |  |
| Commercial charbroiling |  |  | 0.6 |  |

| | | | | |
|---|---|---|---|---|
| Solvents from surface coatings | | | | 15.0 |
| Road paving - cutback asphalt | | | | 16.0 |
| Consumer solvents | | | | 15.0 |
| Storage tanks - gasoline & diesel | | | | 19.0 |
| Waste disposal - landfills | | | | <0.1 |
| Charcoal combustion - campfires | 0.02 | 0.2 | 2.0 | 1.5 |

### *Air Pollutant Concentrations*

The concentrations of ozone between 1983 and 1994 averaged about between 25 and 50 ppb, with peak 1-hr concentrations of up to 80 ppb (Table 9-4). These concentrations fall within a range that may produce visible effects or growth effects on very sensitive species (see Chapter 2), but no reports of injury or growth effects have been noted. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Beta radiation from airborne particles in 1994 was low at the Grand Canyon, averaging between 10 and 20 femtocuries/$m^3$ of air (Arizona Radiation Regulatory Agency). These values should provide a useful “baseline” condition if uranium mining resumes in the region (thousands of mining claims surround the Park; C. Bowman, personal communication).

Van Ee (1979) measured concentrations of CO at the south entrance to the Grand Canyon National Park for 2.5 days in August of 1978. This unpublished report found concentrations varied between 16 ppm (at night) and 44 ppm (early to late morning), with an 8-hour mid-day average of about 30 ppm. The primary standards for CO (Chapter 1) are about 9 ppm for 8 hr and 34 ppm for 1 hr, so workers at the entrance station in 1978 may have been exposed to excessive levels of CO.

Table 9-4. Concentrations of ozone and $SO_2$ for Grand Canyon National Park between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the maximum 3-month Sum60 exposure (ppb-hr in excess of 60 ppb for 12 hr/day); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ 24-hr averages by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1983 | | |
| Mean | 26 | |
| Sum60 | 132 | |
| Max | 66 | |
| 1988 | -- | |
| Mean | | 0.2 |
| Sum60 | | |
| Max | | 1.1 |
| 1989 | | |
| Mean | 43 | 0.2 |
| Sum60 | -- | |
| Max | 68 | 1.0 |
| 1990 | | |
| Mean | 43 | |
| Sum60 | -- | -- |
| Max | 74 | |
| 1991 | | |
| Mean | 46 | 0.2 |
| Sum60 | 21922 | |
| Max | 79 | 1.1 |
| 1992 | | |
| Mean | 44 | 0.1 |
| Sum60 | 10416 | |
| Max | 78 | 0.6 |
| 1993 | | |
| Mean | 46 | 0.2 |
| Sum60 | 7228 | |
| Max | 73 | 2.7 |
| 1994 | | |
| Mean | 49 | 0.1 |
| Sum60 | 12542 | |

| | | |
|---|---|---|
| Max | 79 | 0.9 |

*Visibility*

Equipment has been placed to monitor visibility conditions on the rim and inside the Grand Canyon. One aerosol sampler is on the South Rim at Hopi Point, and a second aerosol sampler is located in the canyon at Indian Gardens. One transmissometer is sighted along the South Rim near Grandview Point, with measurements beginning in December of 1986. Another transmissometer has a sight path from Yavapai Point on the South Rim to the canyon floor, with data collection beginning in December of 1989. The aerosol sampler at Hopi Point began operation in March 1988, the aerosol sampler at Indian Gardens began operation in October 1989. A camera began recording images in October 1979.

The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period December 1986 through February 1994. The seasons used are: spring = March, April, and May; summer = June, July, and August; autumn = September, October, and November; and winter = December, January, and February.

Optical Data - Transmissometer

The transmissometer system consists of two individually-housed primary components: a transmitter (light source) and a receiver (detector). The atmospheric extinction coefficient ($b_{ext}$) at any time can be calculated based on the intensity of light emitted from the source and measured by the receiver (along with the path length between the two). Transmissometers provide continuous, hourly $b_{ext}$ measurements. Weather factors such as clouds and rain can affect transmissometer measurements, but these can be "filtered out" by removing data points with high relative humidities (RH>90%).

The data are presented by season and annual median values, with and without meteorological factors in Table 9-5 Transmissometer Data Summary. The data are presented in units of extinction coefficient in $Mm^{-1}$ and standard visual range in km. Extinction coefficients represent the ability of the atmosphere to scatter and absorb light. Median values with large differences between the extinction values "including weather" and "excluding weather" indicate periods dominated by precipitation. Higher extinction coefficients signify lower visibility. Similarly, season and annual medians with nearly equal "including weather" and "excluding weather" extinctions indicate visibility reduction caused principally by particles.

Table 9-5. Transmissometer data summary for the South Rim of the Grand Canyon for 1987-1994. SVR = visual range; $b_{ext}$ = light extinction coefficient.

| Season Year | Excluding Weather | | Including Weather | |
|---|---|---|---|---|
| | SVR (km) | $b_{ext}$ ($Mm^{-1}$) | SVR (km) | $b_{ext}$ ($Mm^{-1}$) |
| Winter 1987 | 189 | 20 | 173 | 22 |
| Spring 1987 | 153 | 25 | 147 | 26 |
| Summer 1987 | 199 | 19 | 189 | 20 |
| Autumn 1987 | 181 | 21 | 173 | 22 |
| Annual 1987 | 199 | 19 | 287 | 13 |
| Winter 1988 | 287 | 13 | 235 | 16 |
| Spring 1988 | 189 | 20 | 173 | 22 |
| Summer 1988 | 137 | 28 | 132 | 29 |
| Autumn 1988 | 147 | 26 | 141 | 27 |
| Annual 1988 | 173 | 22 | 159 | 24 |
| Winter 1989 | 181 | 21 | 165 | 23 |
| Spring 1989 | 165 | 23 | 159 | 24 |
| Summer 1989 | 147 | 26 | 147 | 26 |
| Autumn 1989 | 210 | 18 | 210 | 18 |
| Annual 1989 | 173 | 22 | 165 | 23 |
| Winter 1990 | 235 | 16 | 222 | 17 |
| Spring 1990 | 147 | 26 | 141 | 27 |
| Summer 1990 | 159 | 24 | 153 | 25 |
| Autumn 1990 | 199 | 19 | 189 | 20 |
| Annual 1990 | 181 | 21 | 165 | 23 |
| Winter 1991 | 189 | 20 | 181 | 21 |
| Spring 1991 | 153 | 25 | 147 | 26 |
| Summer 1991 | 159 | 24 | 159 | 24 |
| Autumn 1991 | 165 | 23 | 153 | 25 |
| Annual 1991 | 165 | 23 | 153 | 25 |
| Winter 1992 | 181 | 21 | 153 | 25 |
| Spring 1992 | 153 | 25 | 147 | 26 |
| Summer 1992 | 165 | 23 | 159 | 24 |
| Autumn 1992 | 181 | 21 | 173 | 22 |
| Annual 1992 | 173 | 22 | 165 | 23 |
| Winter 1993 | 210 | 18 | 147 | 26 |
| Spring 1993 | 165 | 23 | 159 | 24 |
| Summer 1993 | 107 | 36 | 99 | 39 |
| Autumn 1993 | 153 | 25 | 141 | 27 |
| Annual 1993 | 159 | 24 | 153 | 25 |
| Winter 1994 | 235 | 16 | 222 | 17 |
| Spring 1994 | 153 | 25 | 147 | 26 |

| | | | | |
|---|---|---|---|---|
| Summer 1994 | 173 | 22 | 165 | 23 |
| Autumn 1994 | 189 | 20 | 189 | 20 |
| Annual 1994 | 181 | 21 | 173 | 22 |

Visibility tends to be lowest in the spring and summer, when the visibility range is notably lower than in the winter (Table 9-6).

Table 9-6. Standard visual range for the South Rim of Grand Canyon National Park. Seasonal averages for median standard visual range in km from 1986 through 1994.

| Season | Excluding Weather | Including Weather |
|---|---|---|
| Winter | 213 | 187 |
| Spring | 160 | 152 |
| Summer | 156 | 150 |
| Autumn | 178 | 171 |

Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 9-7). To compare this table with the data from Tables 9-6 and 9-5, the "excluding weather" values should be used. In Table 9-7 the data are presented as seasonal and annual 50th and 90th percentile standard visual range for the Grand Canyon. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions. The measured extinction data are used to verify the calculated reconstructed extinction and can also be used to run plume and regional haze models and to analyze visibility trends and conditions.

Because of the larger spatial and temporal range of the aerosol data, the use of the reconstructed extinction data are preferred.

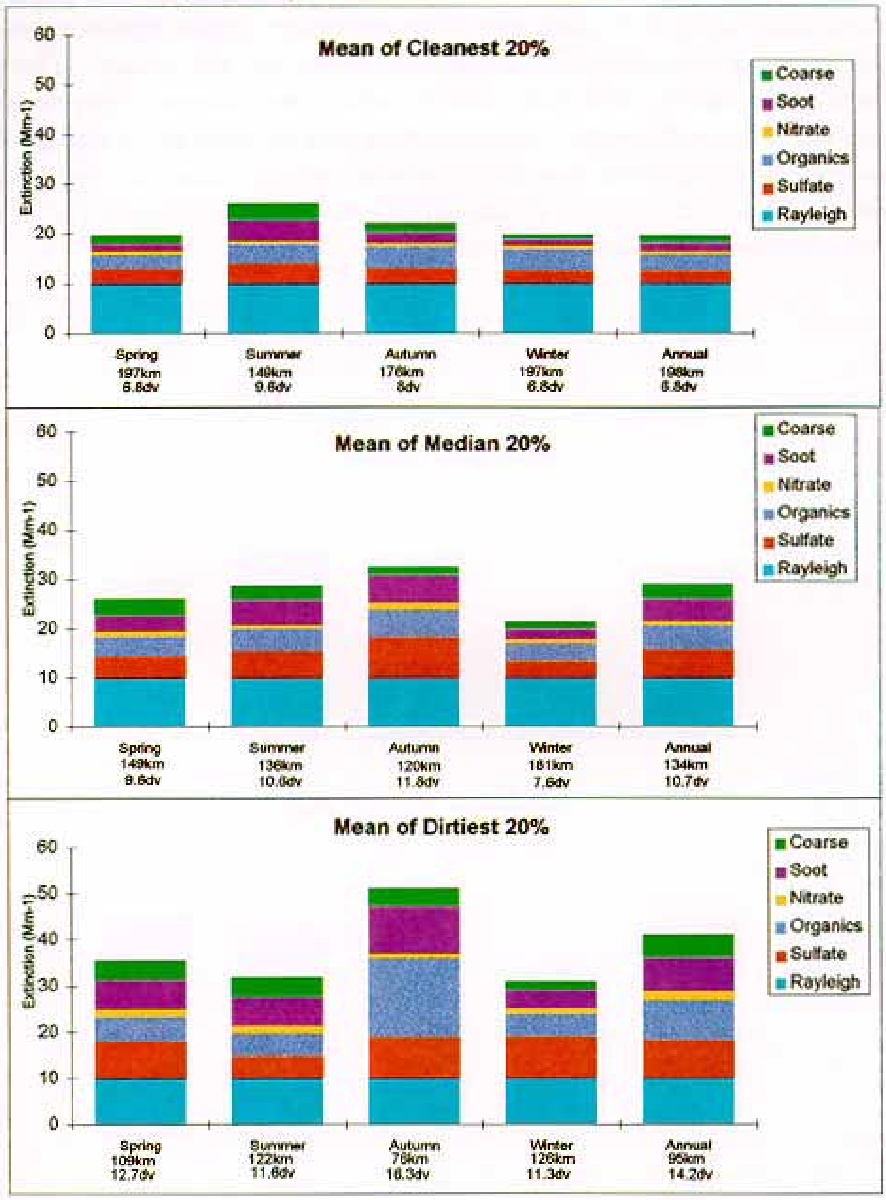
Table 9-7. Reconstructed visual range and light extinction coefficients for Grand Canyon National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentiles, March 1988 - February 1994.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 165 | 23.6 | 225 | 17.3 |
| Spring | 138 | 28.4 | 185 | 22.1 |
| Summer | 120 | 32.6 | 155 | 25.2 |
| Autumn | 132 | 29.6 | 194 | 20.2 |
| Annual | 133 | 29.5 | 203 | 19.3 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at the South Rim to specific aerosol species (Figure 9-2). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of days, mean of median 20% of days, and mean of dirtiest 20%of days. The "dirtiest" and "cleanest" signify highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicates cleaner conditions.

Figure 9-4. Reconstructed extinction budgets for the South Rim, March 1993 through February 1994.

Figure 9-4. Reconstructed extinction budgets for the South Rim, March 1993 through February 1994.



Mean of Cleanest 20%

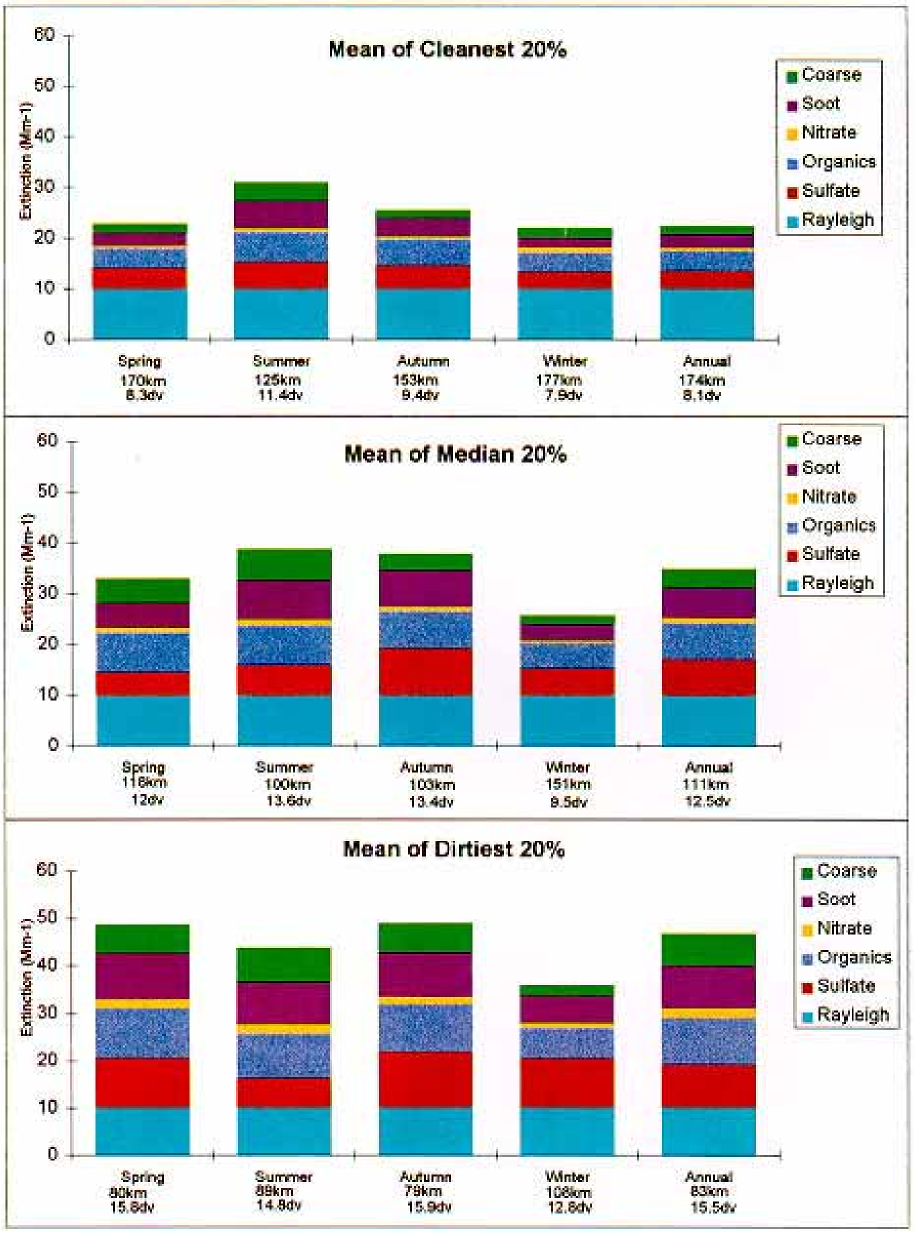
Mean of Median 20%

Mean of Dirtiest 20%

Atmospheric light extinction at the South Rim of the Grand Canyon National Park, like many rural western areas is largely due to sulfate, organic, and soot aerosols. Sulfates, organics, and soot contribute roughly equally to extinction on dirty, median, and clean days annually. At Indian Gardens, sulfates, organics, and soot also contribute roughly equally to extinction on dirty, median, and clean days annually (Figure 9-5). Visibility conditions inside the canyon are 2-4 dv lower than those on the rim during all four seasons based on either aerosol or optical data. The highest median extinctions occur in summer and autumn both in the canyon and on the rim. The lowest median extinctions occur in winter for both locations.

Figure 9-5. Reconstructed extinction budgets for Indian Gardens, March 1993 through February 1994.

**Figure 9-5. Reconstructed extinction budgets for Indian Gardens, March 1993 through February 1994.**



The mean of the median 20% represents the average visibility conditions at the South Rim. On the average days, normal light scattering by the natural gases in the atmosphere contribute about 1/3 of the light scattering, with sulfates and organics contributing another 1/3. The extinction coefficient for the dirtiest 20% of days is almost twice that of the cleanest days, with the exception of summer which shows little variation. The GCVTC (1996) concluded that the dirtiest days involved 60% greater light extinction resulting from human sources of pollution than on the cleanest days.

## Photographs

Three photos are provided to represent the range of visibility conditions for the Grand Canyon transmissometer cumulative frequency data (Figure 9-6). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what the observer sees.

Figure 9-6. Photographs representing visibility conditions at Grand Canyon National Park.

Grand Canyon Air Quality 9-21

Figure 9-6. Photographs representing visibility conditions at Grand Canyon National Park.

**Grand Canyon National Park**
on a “clear” day.

Representative Conditions:
Visual Range: 290 - 380 km
$b_{ext}$: 13 - 10 $\text{Mm}^{-1}$
Haziness: 3 - 0 dv

**Grand Canyon National Park**
on a “average” day.

Representative Conditions:
Visual Range: 170 - 210 km
$b_{ext}$: 23 - 19 $\text{Mm}^{-1}$
Haziness: 8 - 6 dv

**Grand Canyon National Park**
on a “dirty” day.

Representative Conditions:
Visual Range: 60 - 75 km
$b_{ext}$: 65 - 52 $\text{Mm}^{-1}$
Haziness: 19 - 17 dv

## Visibility Projections

The GCVTC (1996) projected likely visibility for Hopi Point through 2040, and the major species responsible for visibility impairment (Figures 9-7, 9-8). Reduced emissions from utilities were projected to reduce light extinction by about 1 $Mm^{-1}$. Light extinction caused by vehicle emissions was projected to decline until approximately 2005, and then increase through 2040. The dirtiest days have more than twice the visibility impairment than the cleanest days, and the bulk of the change results from human-related sources.

Figure 9-7. Projected “baseline” light extinction for the Grand Canyon (Hopi Point) include substantially increased contributions from vehicles (“mobile”) and from road dust (from GCVTC 1996). Left graph is for annual average; right for worst 20% of days.

Figure 9-7. Projected "baseline" light extinction for the Grand Canyon (Hopi Point) include substantially increased contributions from vehicles ("mobile") and from road dust (from GCVTC 1996). Left graph is for annual average; right for worst 20% of days.

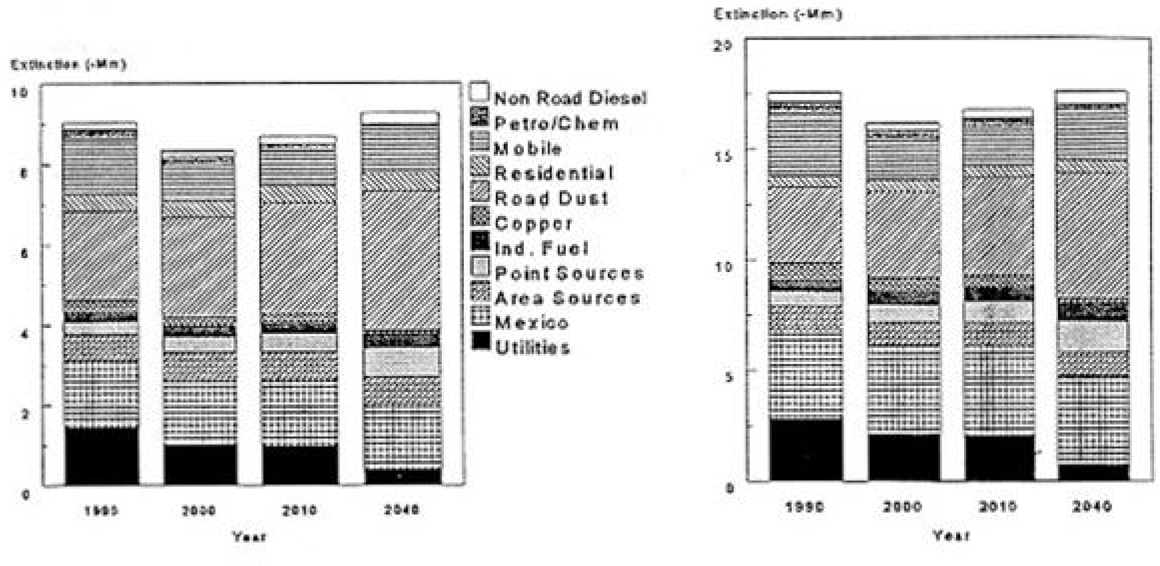
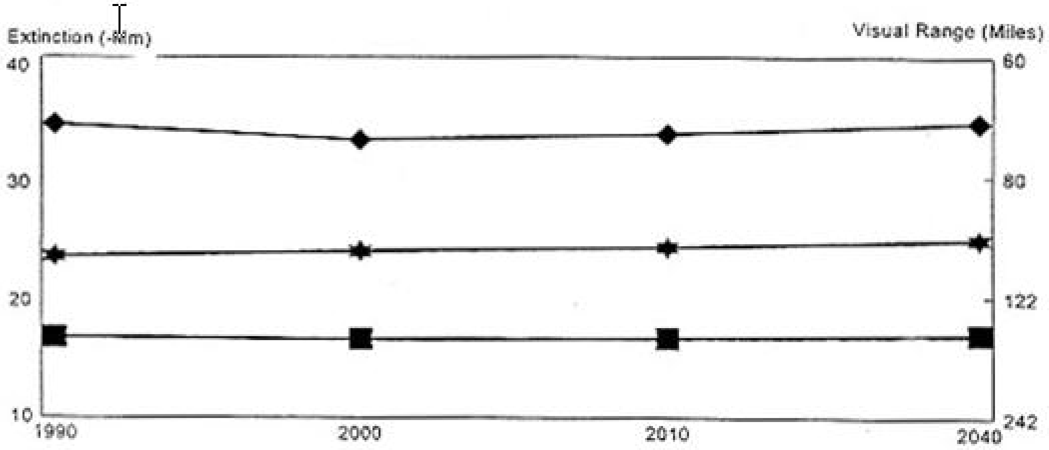


Figure 9-8. Projected “baseline” visibility for the Grand Canyon (Hopi Point) for good, average, and poor visibility conditions (from GCVTC 1996).

Figure 9-8. Projected “baseline” visibility for the Grand Canyon (Hopi Point) for good, average, and poor visibility conditions (from GCVTC 1996).



*Atmospheric Deposition*

The rates of atmospheric deposition for Grand Canyon National Park are low (Table 9-8). Precipitation pH averages about 5.3. Deposition of N averages about 1.5 kg N $ha^{-1}$ $yr^{-1}$, which is similar to the rate of S deposition. No trends are apparent for N or S deposition. Estimates of dry inputs of N and S at Grand Canyon were developed as part of the National Dry Deposition Network (NDDN) for 1990 and 1991, and rates were very low (0.05 kg-N $ha^{-1}$ $yr^{-1}$ as nitrate, and 0.2 kg-S $ha^{-1}$ $yr^{-1}$ as sulfate; Clarke and Edgerton 1993). The estimate for dry deposition of nitrate-N is about 5% of the estimate of wet deposition, and dry deposition of sulfate-S is about 20% of the wet deposition rate. No evidence suggests that such low levels of deposition pose any threat to plants (see Chapter 2). The average pH (on a 5-week basis) tends to track the standard visual range measured by the transmissometers; low (acidic) pH periods tend to have low visibility (C. Bowman, personal communication).

Table 9-8. Atmospheric deposition for Grand Canyon National Park (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentrations (mg/L) | | | Deposition (kg ha$^{-1}$ yr$^{-1}$) | | | | Conductivity (μS/mm) | Precipitation (mm/yr) |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | | |
| 1981 | 0.04 | 0.65 | 1.64 | 0.06 | 0.93 | 2.34 | 5.06 | 1.04 | 143 |
| 1982 | 0.10 | 0.74 | 0.87 | 0.64 | 4.70 | 5.52 | 5.12 | 0.79 | 635 |
| 1983 | 0.09 | 0.68 | 0.70 | 0.47 | 3.52 | 3.63 | 5.25 | 0.61 | 518 |
| 1984 | 0.06 | 0.79 | 0.94 | 0.22 | 2.89 | 3.44 | 5.30 | 0.83 | 366 |
| 1985 | 0.08 | 0.58 | 0.65 | 0.29 | 2.13 | 2.39 | 5.14 | 0.66 | 367 |
| 1986 | 0.07 | 0.70 | 0.71 | 0.26 | 2.61 | 2.64 | 5.23 | 0.68 | 372 |
| 1987 | 0.05 | 0.42 | 0.40 | 0.12 | 1.04 | 0.99 | 5.47 | 0.45 | 247 |
| 1988 | 0.04 | 0.93 | 0.86 | 0.13 | 3.13 | 2.89 | 5.21 | 0.75 | 336 |
| 1989 | 0.16 | 1.01 | 0.64 | 0.33 | 2.08 | 1.32 | 5.45 | 0.66 | 206 |
| 1990 | 0.20 | 1.05 | 0.70 | 0.87 | 4.55 | 3.04 | 5.47 | 0.81 | 434 |
| 1991 | 0.09 | 0.67 | 0.52 | 0.28 | 2.08 | 1.62 | 5.28 | 0.58 | 311 |
| 1992 | 0.13 | 0.74 | 0.49 | 0.60 | 3.39 | 2.25 | 5.28 | 0.58 | 459 |
| 1993 | 0.12 | 0.66 | 0.49 | 0.51 | 2.81 | 2.09 | 5.34 | 0.52 | 426 |
| 1994 | 0.18 | 0.99 | 0.59 | 0.54 | 2.97 | 1.77 | 5.16 | 0.72 | 300 |

### Sensitivity of Plants

No signs of injury from air pollution have been reported for vegetation in or near Grand Canyon National Park. A survey of ponderosa pine found no signs of injury; the plots may be relocatable (L. Mazzu, C. Bowman, personal communication.) Only a few of the Park's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants (such as aspen, and perhaps cottonwood), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

Seasonal water chemistry data for springs and streams draining from both the North and South Rims of the Grand Canyon National Park were presented by Foust and Hoope (1985). These authors noted that water quality monitoring in the Grand Canyon National Park has usually been associated with plans for development of springs or for planned recreational uses of surface waters. Because of the predominance of limestone, dolomite, and gypsum in the rocks of the Grand Canyon, all waters are extremely well-buffered, with the highest ANCs noted during the summer period. The range of pH for all surface waters monitored was 6.9-8.4, with alkalinities in the range of 1000 to 13000 $\mu$eq/L. Many of the geologic formations in the Grand Canyon are high in trace metals, so a number of the surface waters exceed drinking water standards and wildlife habitat acceptability standards for arsenic, selenium and chromium.

### *Amphibians*

In the vicinity of Grand Canyon National Park, researchers have found: Great Basin spadefoot toad (*Scaphiopus intermontanus*), red-spotted frog (*Bufo punctatus*), and the canyon treefrog (*Hyla arenicolor;* Sherbrooke 1966). These species tend to breed in small pools in the sandstone, which tend to be well buffered from acidity. Another listing of amphibians found in the Grand Canyon also included: leopard frog (*Rana pipiens*), tiger salamander (*Ambystoma tigrinum)*, and Woodhouse's Toad (*Bufo woodhousii;* Tomko 1975).

Two amphibian species in Arizona are currently on the State of Arizona threatened list: Chiricahua leopard frog (*Rana chiricahuensis*) and tiger salamander (*Ambystoma tigrinum*). The northern leopard frog is a candidate for State listing. Researchers at the USGS-Biological Resources Division, Colorado Plateau Research Station are conducting surveys of leopard frogs in Arizona, including Grand Canyon to determine the status of this species. Loss of amphibian habitat in Arizona had resulted from development pressures, many of them associated with water development projects.

We conclude there is no evidence to indicate any risk to amphibians from air pollution.

### *Fish*

The closure of the Glen Canyon Dam changed the Colorado River in the Grand Canyon from a warm, muddy river to a cold, clear one. Habitat for some fish species was eliminated, while a valuable sport fishery for exotic species was created. Native species that suffered from these habitat changes include Colorado squawfish (*Ptychocheilus lucius*), bonytail chub (*Gila elegans*), humpback chub (*Gila cypha*), razorback sucker (*Xyrauchen texanus*), roundtail chub (*Gila robusta*), and flannelmouth sucker (*Catostomus insignis*). The life histories and densities of these species in both the main stem of the Colorado River and its tributaries are not well-known. Recent manipulations of flow regimes downstream of the Glen Canyon Dam are designed to improve habitat for these endangered big river fishes. Because of the high pH and ANC in such river systems, these native and nonnative populations are unlikely to be affected by atmospheric deposition.

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Grand Canyon National Park. The monitoring program for air quality is the best in the region, and we have no recommendations for changes. The information from the monitoring program will continue to be fundamental to evaluating the effectiveness of the recommendations from the Grand Canyon Visibility Transport Commission (see Chapter 14). The aquatic systems that have been monitored in Grand Canyon National Park are extremely well buffered with respect to acidification. Most chemical sampling of water resources in Grand Canyon NP has been associated with well-buffered streams and springs that originate in the limestone formations in the Canyon. Little is known about seasonal streams in the North Rim region of the Park. This high-elevation region often develops a seasonal snowpack that melts quickly in the spring. Depending on the hydrology, geology, and soils found in this area, small streams and ponds could experience snowmelt dilution and nitrate pulses in spring. We recommend that areas of the Park that have significant snow accumulation be examined for evidence of resistant bedrock geology that might result in low ANC stream water. If such areas are identified, then monitoring of small headwater streams and ponds is recommended during early snowmelt.

## Park Summary

Visibility is currently the only AQRV known to be impacted by pollution at the Grand Canyon, as with the other National Park Service Class I areas of the Colorado Plateau. Current levels of pollution in northern Arizona are high enough to produce haze and obscure the important vistas of the Park and surrounding areas. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at the Grand Canyon. Visitation to the Grand Canyon National Park is expected to continue to increase in the future, reaching 6 million visitors by 2005 (Rowlands 1993).

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 10.  Great Sand Dunes National Monument

## Introduction

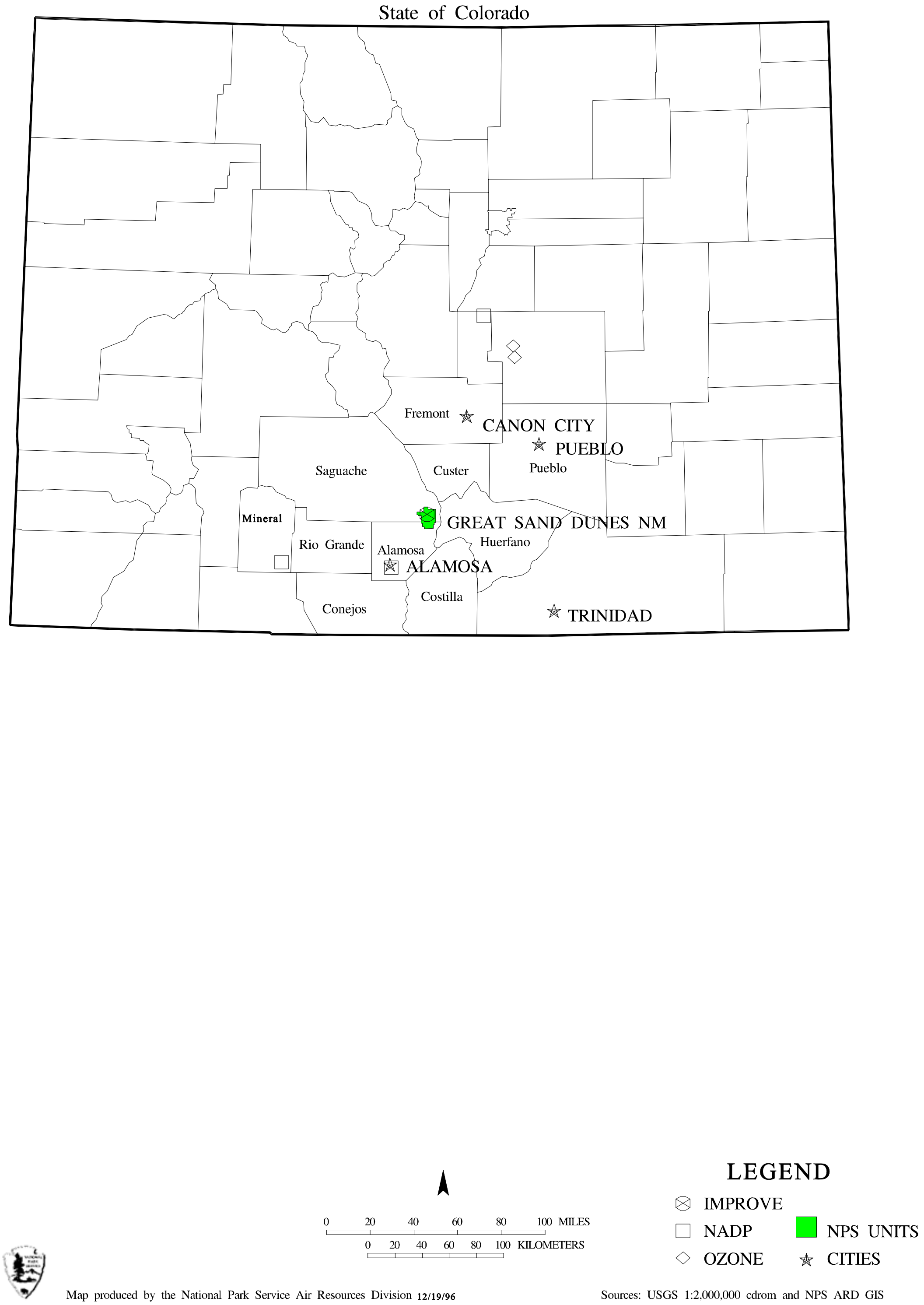
Great Sand Dunes National Monument was established in 1932 to protect the impressive sand dunes that are the highest in the U.S.  The original proclamation cited additional values of scenic, scientific and educational interest.  The landscape includes the abrupt threshold of the spectacular Sangre de Cristo range, canyon-mouth and desert-plain oases, and an unusual mixture of prairie and mountain environments.

The Monument includes about 15,650 ha of which all but 905 ha are federally owned.  In 1976, 13,540 ha of the Monument was designated as Wilderness.  The Great Sand Dunes lie in the San Luis Valley at the southwestern foot of the Sangre de Cristo mountain range in south central Colorado (Figure 10-1).  This area is not geographically considered to be part of the Colorado Plateau. The Monument is bordered on its eastern flank by the Rio Grande National Forest and to the west by the San Luis Valley. The elevation of Great Sand Dunes visitor center is 2,493 m and dunes rise 200 m or more above the valley floor.

### *Geology and Soils*

The sand of the dunes derives from the San Luis basin, where low precipitation since that last glacial period has prevented substantial vegetative cover for 10,000 yr.  Strong southwesterly winds pick up the sand, and then deposit it as the wind is funneled between the peaks of the Sangre de Cristo Range.  Medano, Music and Mosca passes to the east provide the backstop for the transported sand.  The sedimentary sands in the San Luis Valley derive from volcanic parent materials in the surrounding mountains.  Most of the deposited sediment resulted from uplift and erosion of the Sangre de Cristo mountains about 10 million years ago (Chronic 1984).  The soils of the Monument are primarily sands, with dunes covering more than 65% of Great Sand Dunes National Monument.

Figure 10-1. Location of Great Sand Dunes National Monument.



Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

### *Climate*

Great Sand Dunes National Monument has a climate typical of high mountain parks and valleys with cold winters and cool summers because of cold air drainage from surrounding mountains (Figure 10-2). Summers average about 17 $^{o}$C, compared with -6 $^{o}$C in winters. The Monument's proximity to the San Juan mountains to the west results in decreased orographic precipitation as storms from the west unload moisture before moving over this range. This rain shadow effect results in annual precipitation of about 230 mm. The winds at the Monument vary seasonally (Figure 10-3). Winter and spring winds come primarily from the southwest and the east, whereas summer winds come primarily from the east, and autumn winds from all directions except north. The easterly wind in summer is mostly downslope and limited to a narrow area along the mountain front.

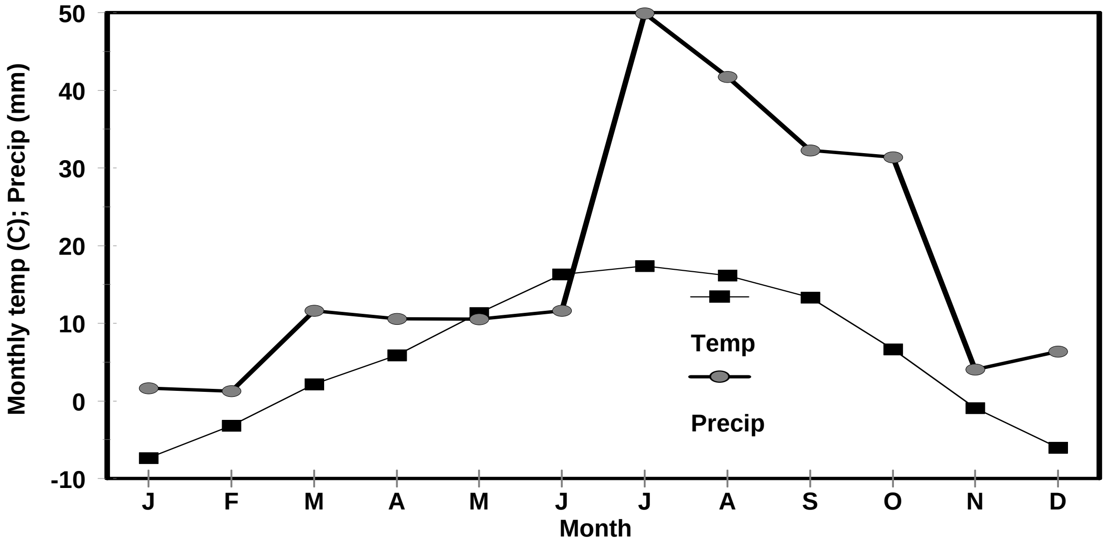
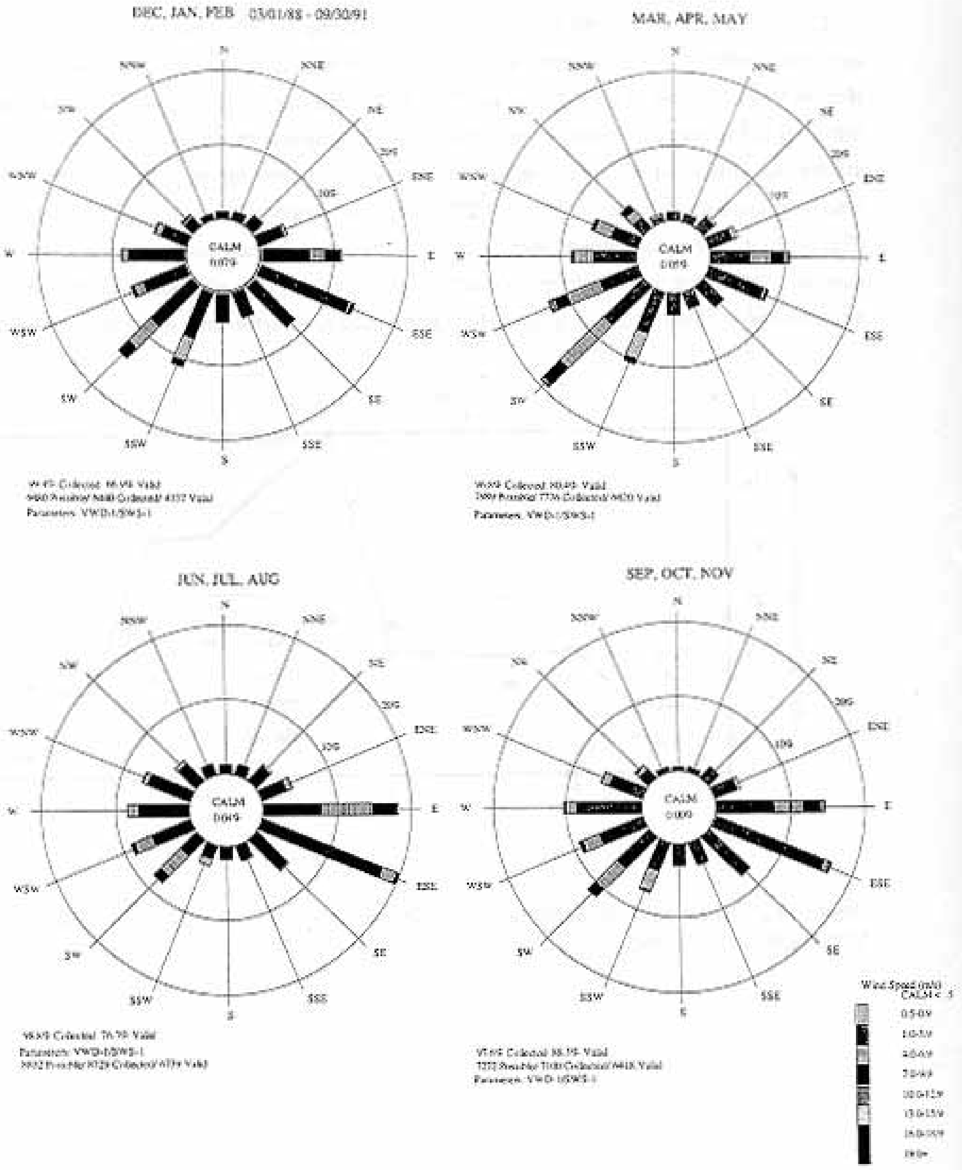


Figure 10-3. Seasonal wind roses for Great Sand Dunes National Monument, 1988-1991.

Figure 10-3. Seasonal wind roses for Great Sand Dunes National Monument, 1988-1991.



### *Vegetation*

Vegetation in the dunes includes scurf pea (*Psoralea lanceolata*), Indian rice grass (*Achnatherun hymenoides*), blowout grass (*Redfieldia flexuosa*), and prairie sunflower (*Helianthus petiolaris*). The Monument as a whole supports such trees as ponderosa pine (*Pinus ponderosa*), pinyon pine (*Pinus edulis*), limber pine (*Pinus flexilis*), white fir (*Abies concolor*), alder (*Alnus tenuifolia)*, aspen (*Populus tremuloides*), serviceberry (*Amelanchier alnifolia*), mountain maple *(Acer glabrum*), and many shrubs, grasses and forbs. *Cleome multicaulus* is the only NPS plant species of special concern (F. Bunch, personal communication). Complete lists for plants and lichens are contained in NPFlora and NPLichen.

## Air Quality

Air quality monitoring for Great Sand Dunes National Monument consists of data from 1988-1991 for ozone concentration, NADP monitoring in Alamosa, Colorado (30 km away) from 1980 to the present, $SO_2$ measurements from 1988-1992, and IMPROVE monitoring for visibility from 1988 to the present (particle sampling at Morris Gulch, camera near the landing strip).

### *Emissions*

Table 10-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 10 counties surrounding Great Sand Dunes National Monument. Emissions of $SO_x$ from Pueblo County are the highest (particularly from the Comanche Plant of Public Service Company), but Great Sand Dunes probably receives very little of this material because the sources are across the Sangre de Cristo range and the prevailing wind direction (from the west) is away from the Monument. No information is available to relate these emissions to local air quality at Great Sand Dunes, or to apportion air quality impairment to local and regional sources.

Table 10-1. Emissions (tons/day) for counties surrounding Great Sand Dunes National Monument (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| Alamosa, CO | 18.58 | 0.77 | 2.13 | 5.99 | 9.1 | 0.20 |
| Conejos, CO | 21.22 | 1.71 | 2.44 | 10.65 | 11.5 | 0.24 |
| Costilla, CO | 8.95 | 0.70 | 0.96 | 8.74 | 4.9 | 0.10 |
| Custer, CO | 5.08 | 0.51 | 0.50 | 7.65 | 2.5 | 0.06 |
| Fremont, CO | 40.65 | 0.93 | 11.62 | 21.35 | 18.7 | 15.50 |
| Huerfano, CO | 10.86 | 1.21 | 1.07 | 14.26 | 4.9 | 0.17 |
| Mineral, CO | 2.75 | 0.31 | 0.25 | 6.42 | 1.4 | 0.03 |
| Pueblo, CO | 155.21 | 2.07 | 52.87 | 12.30 | 45.2 | 35.22 |
| Rio Grande, CO | 22.53 | 1.00 | 2.47 | 7.95 | 11.1 | 0.24 |
| Saguache, CO | 10.52 | 1.94 | 1.23 | 26.26 | 6.1 | 0.12 |

*Air Pollution Concentrations*

The concentrations of ozone in 1988 to 1992 averaged about 40 ppb, with peak 1-hr concentrations of 65 to 85 ppb (Table 10-2). These concentrations fall within a range that may produce visible effects or growth effects on very sensitive species (see Chapter 2), but no reports of injury or growth effects have been noted. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Table 10-2. Concentrations (ppb) of ozone and $SO_2$ for Great Sand Dunes National Monument. For ozone, upper value is mean daily concentration (ppb); middle number is the maximum 3-month Sum60 exposure (ppb-hr in excess of 60 ppb for 12 hr/day); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ 24-hr averages by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1988 | | |
| Mean | 40 | 0.1 |
| Sum60 | 1174 | |
| Max | 76 | 0.3 |
| 1989 | | |

| | | |
|---|---|---|
| Mean | 41 | 0.1 |
| Sum60 | 752 | |
| Max | 63 | 0.3 |
| 1990 | | |
| Mean | 42 | 0.1 |
| Sum60 | 4867 | |
| Max | 70 | 1.1 |
| 1991 | | |
| Mean | 41 | 0.1 |
| Sum60 | 7167 | |
| Max | 77 | 0.2 |
| 1992 | | |
| Mean | | 0.0 |
| Sum60 | | |
| Max | | 0.0 |

*Visibility*

Great Sand Dunes National Monument is part of the IMPROVE Monitoring Network. The aerosol sampler began operation in May 1988 and the camera operated from July 1987 to April 1995. The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period May 1988 through February 1994, based on seasons of spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). No transmissometer data are available, but visual ranges have been estimated based on aerosol sampling.

Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 10-3). The best visibility occurs during the winter. The reconstructed extinction in Table 10-4 is presented as seasonal and annual 50th and 90th percentile standard visual range for Great Sand Dunes. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season.

Table 10-3. Reconstructed visual range and light extinction coefficients for Great Sand Dunes National Monument, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentiles, March 1988 - February 1994.

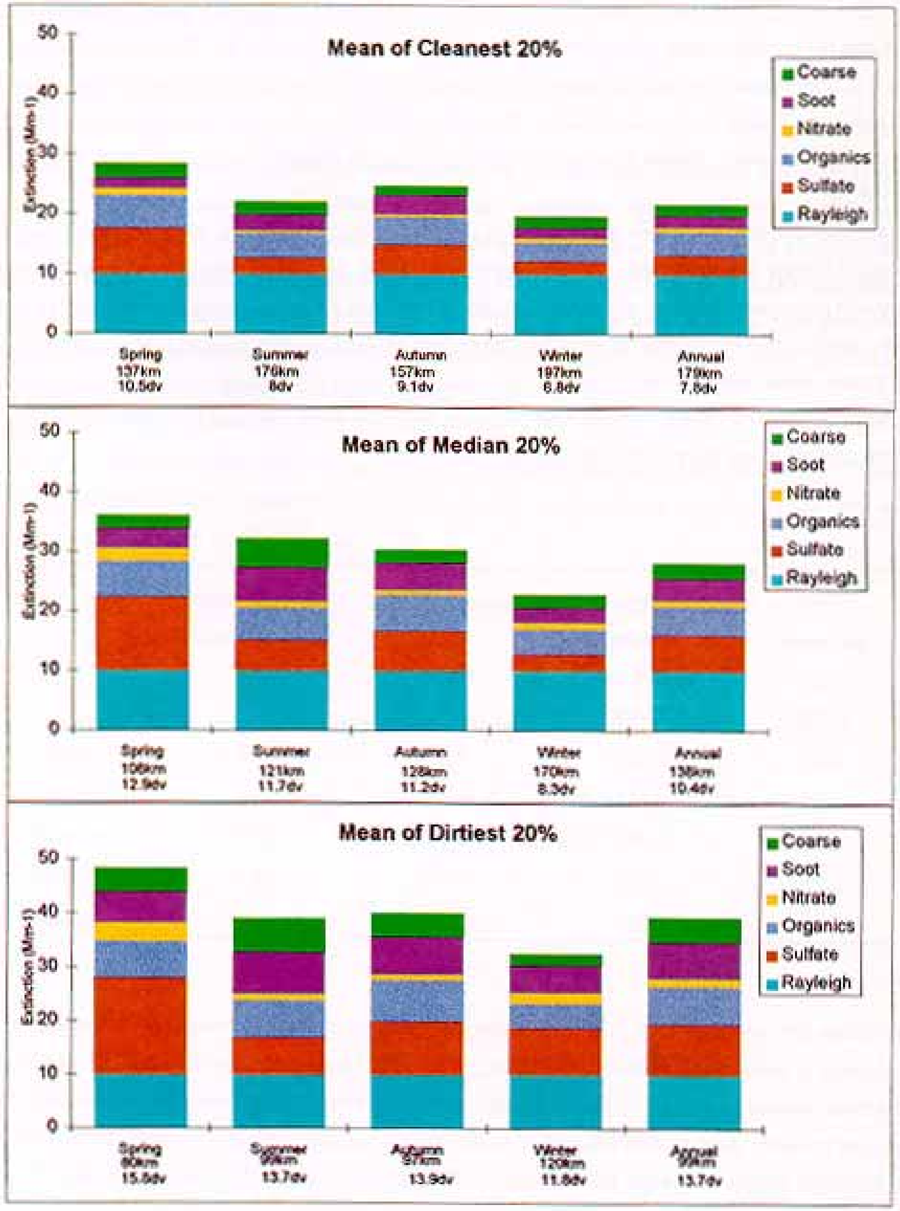
| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 148 | 26.4 | 190 | 20.5 |
| Spring | 102 | 38.3 | 144 | 27.1 |
| Summer | 120 | 32.6 | 161 | 24.3 |
| Autumn | 135 | 29.0 | 177 | 22.1 |
| Annual | 125 | 31.2 | 175 | 22.4 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Great Sand Dunes to specific aerosol species (Figure 10-4). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of days, mean of median 20% of days, and mean of dirtiest 20% of days. The "dirtiest" and "cleanest" signify highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicate cleaner conditions.

Atmospheric light extinction at Great Sand Dunes National Monument, like many rural western areas, is largely due to sulfate, organic, and soot aerosols. In pre-industrial times, visibility would vary with patterns in weather, winds (and the effects of winds on coarse particles), and smoke from fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions, but the cleanest 20% of the days probably approach natural conditions (GCVTC 1996). Smoke from frequent fires may have reduced pre-settlement visibility below current levels during the summer months.

Figure 10-4. Reconstructed extinction budgets for Great Sand Dunes National Monument, March 1993 through February 1994.

**Figure 10-4. Reconstructed extinction budgets for Great Sand Dunes NM, March 1993 through February 1994.**



## Photographs

Three photos are provided to represent the range of visibility conditions for the Great Sand Dunes camera data (Figure 10-5). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what the observer sees.

Figure 10-5. Photographs representing visibility conditions at Great Sand Dunes National Monument.

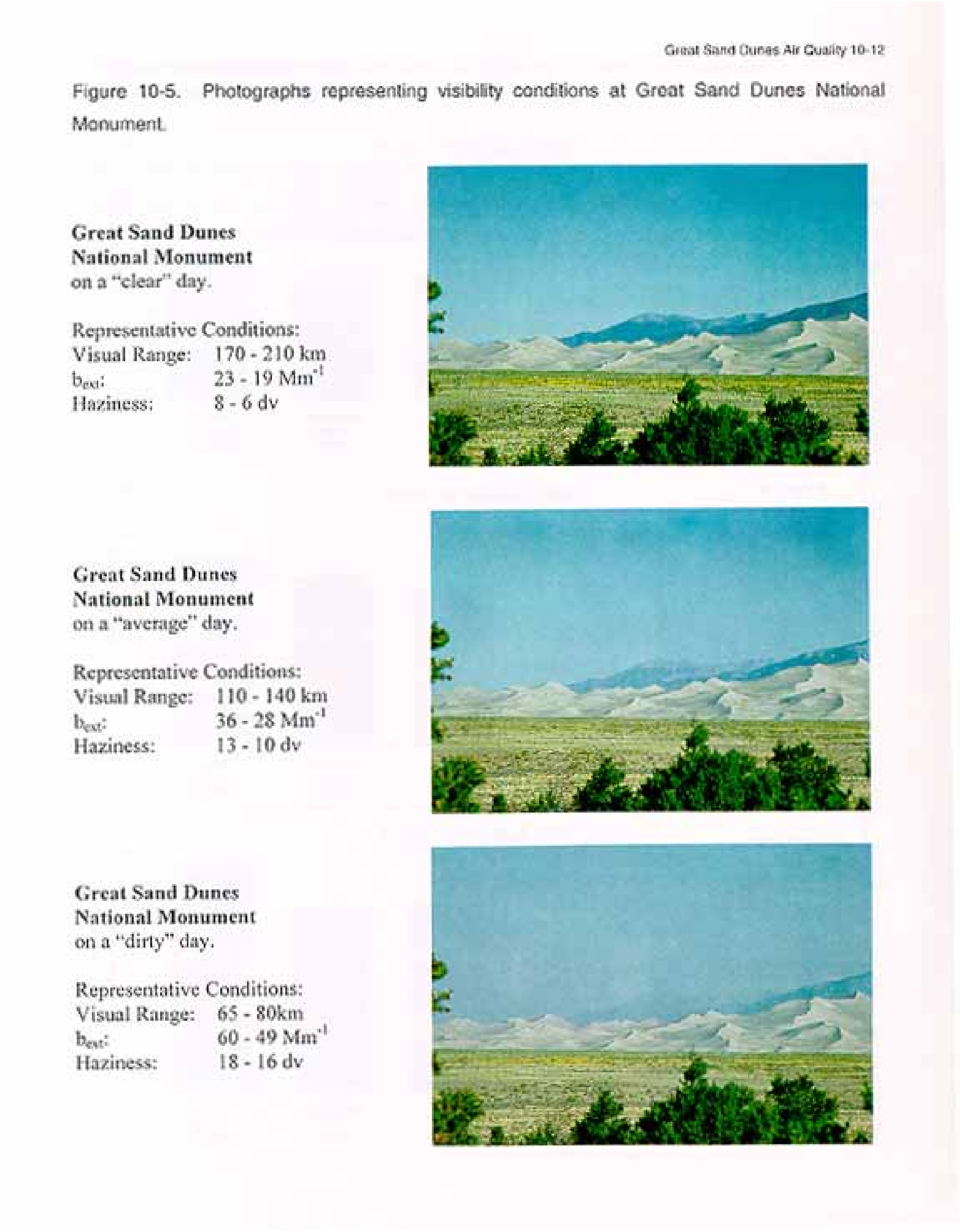


Figure 10-5. Photographs representing visibility conditions at Great Sand Dunes National Monument.

**Great Sand Dunes National Monument**
on a "clear" day.

Representative Conditions:
Visual Range: 170 - 210 km
$b_{ext}$: 23 - 19 $Mm^{-1}$
Haziness: 8 - 6 dv

**Great Sand Dunes National Monument**
on a "average" day.

Representative Conditions:
Visual Range: 110 - 140 km
$b_{ext}$: 36 - 28 $Mm^{-1}$
Haziness: 13 - 10 dv

**Great Sand Dunes National Monument**
on a "dirty" day.

Representative Conditions:
Visual Range: 65 - 80km
$b_{ext}$: 60 - 49 $Mm^{-1}$
Haziness: 18 - 16 dv

### *Atmospheric Deposition*

The rates of atmospheric deposition for Alamosa, Colorado (about 30 km southwest of the Monument) are low (Table 10-4). Precipitation pH averages about 5.5, which is higher than most other NADP sites on the Colorado Plateau, probably reflecting the high alkalinity of the soils in the San Luis Valley. Deposition of N averages only 0.5 kg N $ha^{-1}$ $yr^{-1}$, which is similar to the rate of S deposition. No trend is apparent for the concentration or deposition of N or S. There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2).

Table 10-4. Atmospheric deposition for Alamosa, Colorado, near Great Sand Dunes National Monument (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentrations (mg/L) | | | Deposition (kg $ha^{-1}$ $yr^{-1}$) | | | | Conductivity (μS/mm) | Precipitation (mm/yr) |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | | |
| 1980 | 0.38 | 0.93 | 1.33 | 0.41 | 1.00 | 1.44 | 5.68 | 0.88 | 108 |
| 1981 | 0.41 | 1.03 | 1.81 | 0.93 | 2.34 | 4.11 | 5.24 | 1.34 | 227 |
| 1982 | 0.43 | 0.89 | 1.51 | 0.54 | 1.11 | 1.89 | 5.59 | 0.99 | 125 |
| 1983 | 0.51 | 1.15 | 1.39 | 0.94 | 2.13 | 2.57 | 5.58 | 1.00 | 185 |
| 1984 | 0.21 | 0.79 | 1.11 | 0.38 | 1.43 | 2.00 | 5.51 | 0.86 | 180 |
| 1985 | 0.19 | 0.55 | 0.75 | 0.48 | 1.38 | 1.88 | 5.29 | 0.66 | 251 |
| 1986 | 0.21 | 0.66 | 1.09 | 0.42 | 1.33 | 2.19 | 5.28 | 0.88 | 201 |
| 1987 | 0.22 | 0.71 | 0.75 | 0.37 | 1.20 | 1.27 | 5.42 | 0.67 | 169 |
| 1988 | 0.12 | 0.66 | 0.99 | 0.17 | .91 | 1.37 | 5.49 | 0.79 | 138 |
| 1989 | 0.47 | 1.21 | 1.19 | 0.52 | 1.34 | 1.32 | 5.59 | 0.98 | 111 |
| 1990 | 0.27 | 0.68 | 0.86 | 0.78 | 1.96 | 2.48 | 5.50 | 0.68 | 288 |
| 1991 | 0.19 | 0.77 | 1.10 | 0.36 | 1.46 | 2.08 | 5.35 | 0.97 | 189 |
| 1992 | 0.28 | 0.59 | 0.52 | 0.64 | 1.35 | 1.19 | 5.70 | 0.54 | 229 |
| 1993 | 0.26 | 0.69 | 0.61 | 0.65 | 1.72 | 1.52 | 5.56 | 0.59 | 249 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1994 | 0.24 | 0.74 | 0.73 | 0.44 | 1.34 | 1.32 | 5.25 | 0.69 | 181 |

## Sensitivity of Plants

No air pollution injury has been reported for vegetation in or near Great Sand Dunes National Monument. Only a few of the Monument's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Monument. Based on the ozone concentrations required to affect very sensitive plants (such as aspen), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

Water resources in the Great Sand Dunes National Monument include Medano, Mosca, Cold and Sand Creeks. Because of the sandy nature of the Monument, these streams sink into the sand and disappear within the Monument's boundaries. Medano Creek is sampled by the U.S. Geological Survey (USGS) as part of the National Water Quality Assessment Program (NAWQA). Water samples collected from September 1992 through January 1995 showed a range in pH from 7.0-8.7, with a range in alkalinity values of 22-47 mg/L (as CaCO3, = 440 to 940 μeq/L ANC). Water chemistry has been monitored for Medano Creek as part of the USGS NAWQA Program; pH values between 1992 and 1995 were 7.0 to 8.3, with ANC from 440 μeq/L to 980 μeq/L. These values indicate a relatively well-buffered stream, with sufficient ANC to prevent chemical change due to acidic deposition.

### *Amphibians*

The species list for Great Sand Dunes includes: Great Plains toad *(Bufo cognatus*), the plains spadefoot toad (*Scaphiopus bombifrons*), and tiger salamander *(Ambystoma tigrinum*). Although there are few data on amphibian species abundance in Great Sand Dunes, the northern leopard frog (*Rana pipiens*) is declining the San Luis Valley of Colorado, a region immediately adjacent to the Monument (Navo, personal communication). Given the chemistry of surface waters in the

Monument, it is unlikely that acidification is affecting the resident amphibian populations.

### Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Great Sand Dunes National Monument. Monitoring of air quality at Great Sand Dunes National Monument involves an IMPROVE site and NADP sampling in nearby Alamosa. No ozone monitoring occurs at Great Sand Dunes; we anticipate no critical AQRV issues about ozone, but long-term monitoring at this Class I site may be useful given the lack of ozone monitoring in any nearby locations.

Currently monitored stream reaches in the Monument are not at risk to chronic acidification due to deposition. However, upper stream reaches that drain lands managed by the USFS might have lower ANCs than those monitored at lower elevations. Snowmelt runoff could have an influence on stream water quality in the spring. More needs to be known about the contributing areas for Monument streams and patterns of flow before a monitoring scheme could be developed for water quality. Since the USGS researchers have collected data in the Monument as part of the NAWQA program, we recommend that Monument staff review the existing data with these researchers to determine the likelihood that more dilute waters might be found upstream of the current stations. These headwater reaches might provide information on snowmelt runoff nitrate in stream water, indicating the need for annual sampling during this sensitive period.

### Park Summary

Visibility is currently the only AQRV known to be impacted by pollution, as with the other National Park Service Class I areas of the Colorado Plateau. Current levels of pollution in southern Colorado are lower than across most of the Colorado Plateau. However, any increase in aerosols would reduce visibility further.

Little information has been collected on air pollution effects on the Park’s biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 11. Mesa Verde National Park

## Introduction

Mesa Verde National Park was established in 1906, three weeks after the passage of the 1906 Antiquities Act. The enabling legislation states that Mesa Verde National Park was established "to preserve from injury or spoilation the unusual and large number of ruins and other works and relics of prehistoric or primitive man, among which are the largest and most spectacular cliff dwellings in the United States." The Park's Anasazi cliff dwellings are some of the best preserved in the region.

Mesa Verde National Park is entirely within Montezuma County in southwestern Colorado, just west of the La Plata mountains, and southeast of the center of the Colorado Plateau (Figure 11-1). The Park is bounded to the north by the Montezuma Valley and the North Escarpment, to the east by the Mancos River Valley and to the south and west by the Ute Mountain Ute Indian Reservation. After several boundary changes in 1913, 1932 and 1963, the current size of the Park is 21,100 ha of which only 94 ha are non-federal. In 1976, 3,280 ha were given wilderness status and in 1978 Mesa Verde National Park was declared an World Heritage Site.

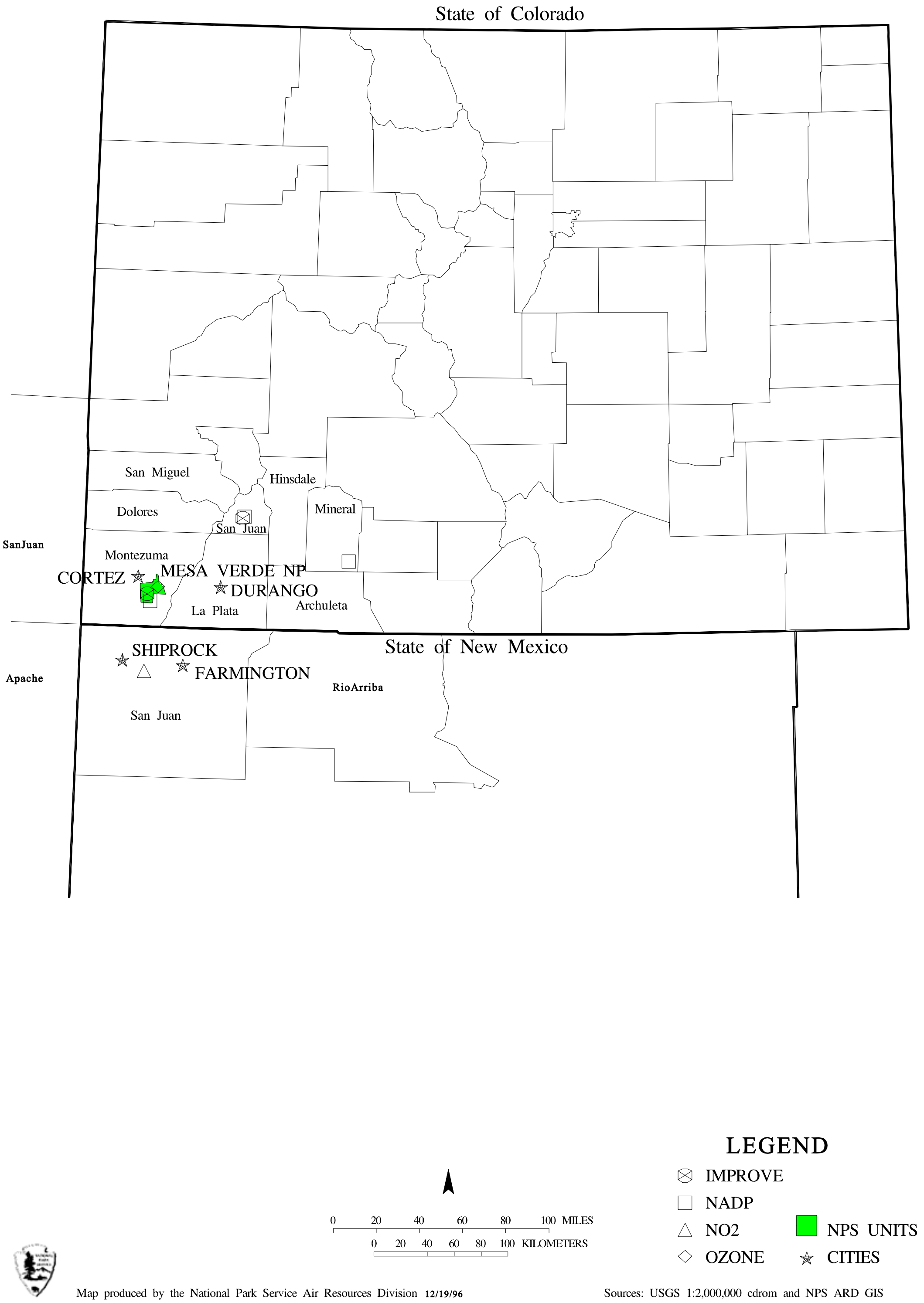
The archeological remains of the Anasazi are the main attraction for the Park. The Mesa Verde Branch of the San Juan Anasazi inhabited the four-corners region from 400 A.D. to almost 1300 A.D. They left some 4,000 archeological sites. Estimates for peak pre-historic population for the area put the number of inhabitants at around 15,000.

### *Geology and Soils*

The Mesa Verde is an erosional remnant rising 500 to 650 m above the Dolores Plateau. The Mesa Verde itself ranges from about 2,000 to 2,800 m and includes about 3,000 square km of the San Juan Basin. This tableland is deeply incised with deep vertical-walled canyons that span the Menefee Formation, the Point Lookout Sandstone and the Mancos Shale. In some places, where erosion has been moderate, the Menefee is capped by the Cliff House Sandstone of marine origin. The Mesa Verde Group dates from the late Cretaceous Period, and is comprised of the 120 m thick Cliff House sandstone, the 100-250 m thick Menefee Formation (deposited in a floodplain or coastal swamp environment), and the 120 m thick Point Lookout Sandstone (marine deposit). The massive, soft, dark Mancos Shale is exposed along the North Escarpment of the Mesa; this formation was deposited in Cretaceous seas, and is characteristically barren of vegetation (Chronic

1988).

Figure 11-1. Location of Mesa Verde National Park.



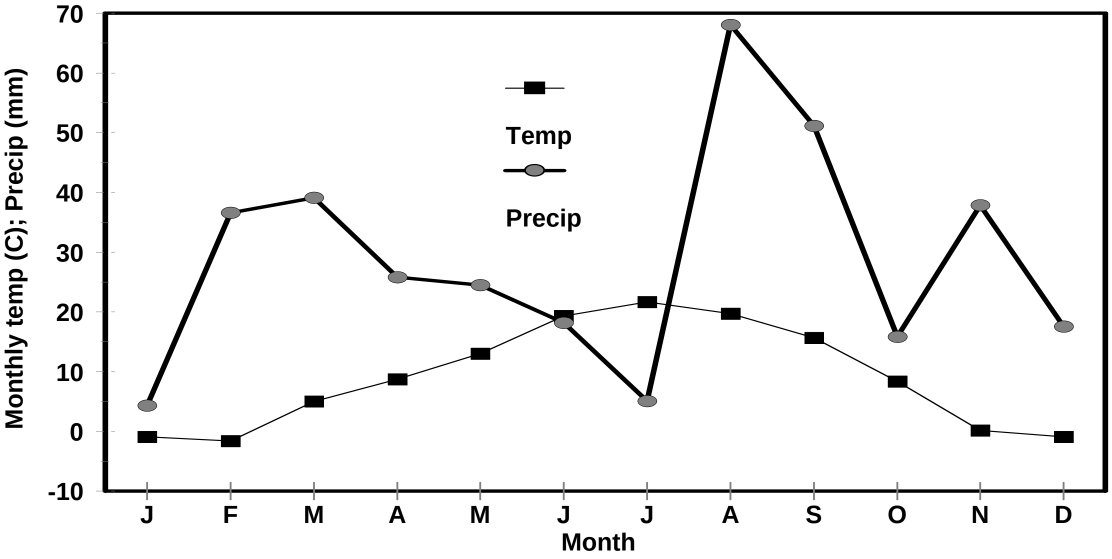
Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

The soils found in Mesa Verde National Park can be broken down into 4 main categories. The basalt rockland complex is composed largely of rocky outcrops, cliffs and steep talus slopes. The rough broken land complex is composed largely of infertile shallow soils, with some pockets of deeper, more fertile soil. This category provides sediment, through runoff, for the sandstone outcrop complex which is composed of highly stratified sandy soils with low moisture-holding capacity. Some of the soils in this complex are deeper, well developed and very fertile. The last category, the sandstone outcrop/stonyland complex, is composed of moderately deep to deep soils developed in place on the mesa bedrock with loess deposits. This complex offers the largest area of arable soil and maintains topsoil textures that range from fine and very fine sandy loams to loams. Clay loam subsoils predominate with sandy clay loams interspersed.

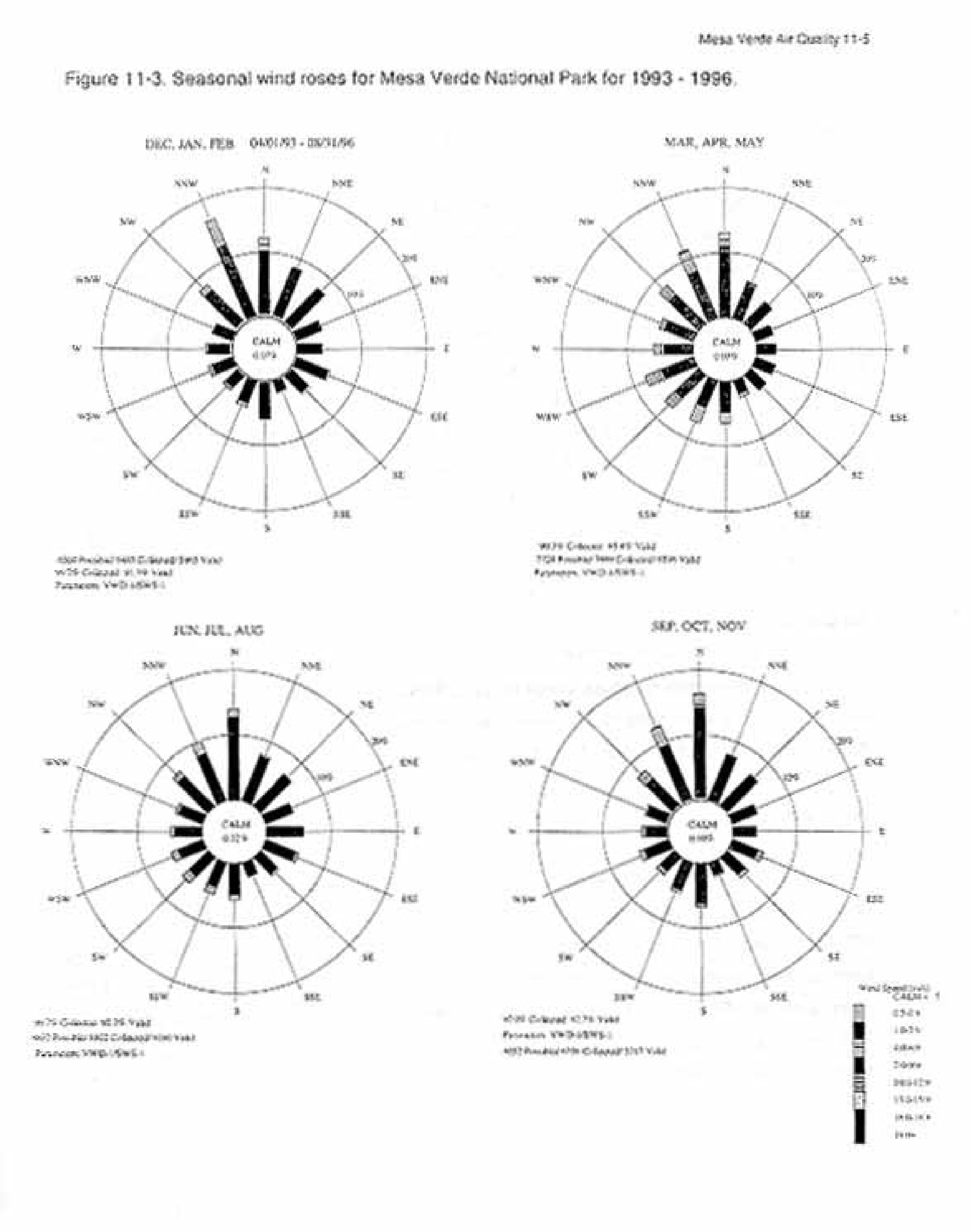
*Climate*

The climate of Mesa Verde is generally cool and semi-arid (Figure 11-2). Annual average precipitation is about 460 mm while monthly average temperatures range from 22 °C in July to -2 °C in January. Highs can reach 37 °C in summer months. The annual average of 2 m of snowfall provides critical moisture for vegetation growth in spring and summer. Thunderstorms are common



in the summer. Winds come primarily from the north/northwest, with little seasonal variation (Figure 11-3).

Figure 11-3. Seasonal wind roses for Mesa Verde National Park for 1993 - 1996.



### *Vegetation*

The vegetation of Mesa Verde National Park is typical of the arid plateau regions of the southwestern U.S. Six distinct vegetation types are recognized in Mesa Verde. The two major community types are pinyon (*Pinus edulis*) / juniper (*Juniperus osteosperma*) and chaparral (dominated by Gambel oak (*Quercus gambelii*) and serviceberry (*Amelanchier alnifolia*)), each comprising almost half of the Park's vegetation. Minor portions of the Park are covered by Douglas-fir (*Pseudotsuga menzeisii*)/ ponderosa pine (*Pinus ponderosa*) woodlands; by grassland communities with western wheatgrass (*Pascopyrum smithii*), blue grama (*Bouteloua gracilis*), needle and thread grass (*Stipa comata*), and mutton grass (*Poa fendeleriana*); by upland sagebrush (*Artemisia tridentata*) communities; and by a semi-desert scrubland that resembles a sparse version of chaparral. Species of special concern for the NPS are *Astagalus schmolii*, *Astragalus deterior*, *Hachelia grassialenta*, and *Lliamna rivuraris* (M.Colyer, personal communication). Mesa Verde National Park may be somewhat unique in the region because grazing has been excluded from the Park boundaries for 60 yrs. NPFlora provides a complete listing of plant species found in the Park while NPLichen and Nash (1991) provide listings of lichen species.

## **Air Quality**

Air quality monitoring for Mesa Verde National Park includes ozone data from 1993-present, NADP monitoring from 1981 to the present, sulfur dioxide measurements from 1991-1992, and IMPROVE monitoring for visibility from 1988 to the present.

### *Emissions*

Table 11-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 11 counties surrounding Mesa Verde National Park. The greatest $SO_x$ emissions come from San Juan County (Arizona Public Service's 4-Corners Plant and Public Service Company's San Juan Generating Plant). The high emissions in Apache County, Arizona, come primarily from a Salt River Project plant. No information is available to relate these emissions to local air quality at Mesa Verde, or to apportion Mesa Verde's air quality impairment to local and regional sources.

Table 11-1. Emissions (tons/day) for counties surrounding Mesa Verde National Park (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Archuleta, CO | 11.5 | 0.7 | 1.2 | 15 | 6 | 0.1 |
| Dolores, CO | 4.0 | 0.5 | 1.1 | 10 | 34 | 0.1 |
| Hinsdale, CO | 1.6 | 0.4 | 0.1 | 5 | 1 | 0.0 |
| La Plata, CO | 57.6 | 1.4 | 16.8 | 16 | 79 | 0.6 |
| Montezuma, CO | 35.0 | 1.6 | 4.6 | 18 | 82 | 0.6 |
| San Juan, CO | 2.0 | 0.1 | 0.3 | 2 | 14 | 0.0 |
| San Miguel, CO | 11.5 | 0.7 | 1.3 | 11 | 45 | 0.1 |
| San Juan, UT | 40.8 | 0.7 | 3.9 | 103 | 405 | 0.5 |
| Apache, AZ | 138.5 | 3.2 | 83.3 | 118 | 554 | 64.0 |
| San Juan, NM | 166.6 | 1.2 | 196.6 | 50 | 372 | 175.5 |
| Rio Arriba, NM | 91.0 | 1.3 | 15.9 | 72 | 264 | 0.13 |

### *Air Pollutant Concentrations*

The concentrations of ozone in 1993 and 1994 averaged about 43 ppb, with peak 1-hr concentrations of about 70 ppb (Table 11-2). The peak concentrations are at the lowest end of the range that may produce visible effects or growth effects on very sensitive species (see Chapter 2), but the cumulative (sum60) exposures are quite low. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Table 11-2. Concentrations of ozone and $SO_2$ for Mesa Verde National Park between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the maximum 3-month Sum60 exposure (ppb-hr for 12 hr/day); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ 24-hr averages by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1991 | -- | |
| Mean | | 0.2 |
| Sum60 | | |
| Max | | 1.0 |
| 1992 | -- | |
| Mean | | 0.3 |
| Sum60 | | |
| Max | | 1.9 |
| 1993 | | -- |
| Mean | 41 | |
| Sum60 | 893 | |
| Max | 67 | |
| 1994 | | -- |
| Mean | 45 | |
| Sum60 | 7023 | |
| Max | 72 | |

### *Visibility*

Visual air quality in Mesa Verde National Park has been monitored using a transmissometer, aerosol sampler and a camera. The transmissometer operated (near Spruce Canyon) from September 1988 to June 1993, the aerosol sampler began operation in March 1988 (also near

Spruce Canyon), and the camera operated from September 1979 to April 1995 (from Navajo Hill). The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for the period September 1988 through February 1994, based on seasons of spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

## Optical Data - Transmissometer

The transmissometer system consists of two individually-housed primary components: a transmitter (light source) and a receiver (detector). The atmospheric extinction coefficient ($b_{ext}$) at any time can be calculated based on the intensity of light emitted from the source and that measured by the receiver (along with the path length between the two). Transmissometers provide continuous, hourly $b_{ext}$ measurements. Weather factors such as clouds and rain can affect transmissometer measurements, but these can be "filtered out" by removing data points with high relative humidities (RH>90%).

The data are presented by season and annual median values, with and without meteorological factors, in Table 11-3. The data are presented in units of extinction coefficient in $Mm^{-1}$ and standard visual range in km. Extinction coefficients represent the ability of the atmosphere to scatter and absorb light. Median values with large differences between the extinction values "including weather" and "excluding weather" indicate periods dominated by precipitation. Higher extinction coefficients signify lower visibility. Similarly, season and annual medians with nearly equal "including weather" and "excluding weather" extinctions indicate visibility reduction caused principally by particles.

Table 11-3. Transmissometer data summary for Mesa Verde National Park for 1988-1993. (SVR = standard visual range; $b_{ext}$ = light extinction coefficient.)

| Season Year | Excluding Weather | | Including Weather | |
|---|---|---|---|---|
| | SVR (km) | $b_{ext}$ ($Mm^{-1}$) | SVR (km) | $b_{ext}$ ($Mm^{-1}$) |
| Autumn 1988 | 141 | 27 | 131 | 29 |

| | | | | |
|---|---|---|---|---|
| Winter 1989 | 158 | 24 | 146 | 26 |
| Spring 1989 | 123 | 31 | 113 | 34 |
| Summer 1989 | 109 | 35 | 106 | 36 |
| Autumn 1989 | 106 | 36 | 104 | 37 |
| Annual 1989 | 119 | 32 | 113 | 34 |
| Winter 1990 | 136 | 28 | 127 | 30 |
| Spring 1990 | 113 | 34 | 106 | 36 |
| Summer 1990 | 98 | 39 | 94 | 41 |
| Autumn 1990 | -- | -- | -- | -- |
| Annual 1990 | 123 | 31 | 109 | 35 |
| Winter 1991 | -- | -- | -- | -- |
| Spring 1991 | -- | -- | -- | -- |
| Summer 1991 | 127 | 30 | 127 | 30 |
| Autumn 1991 | 131 | 29 | 123 | 31 |
| Annual 1991 | 131 | 29 | 123 | 31 |
| Winter 1992 | 165 | 23 | 136 | 28 |
| Spring 1992 | 131 | 29 | 127 | 30 |
| Summer 1992 | 113 | 34 | 113 | 34 |
| Autumn 1992 | 119 | 32 | 116 | 33 |
| Annual 1992 | 127 | 30 | 119 | 32 |
| Winter 1993 | 127 | 30 | 68 | 57 |
| Spring 1993 | 116 | 33 | 109 | 35 |

Visibility tends to be highest in winter for low-humidity days, and lowest during the summer (Table 11-4).

Table 11-4. Standard visual range for Mesa Verde National Park. Seasonal averages for median standard visual range in km from September 1988 - May 1993.

| Season | Excluding Weather | Including Weather |
|---|---|---|
| Winter | 146 | 119 |
| Spring | 121 | 114 |
| Summer | 112 | 110 |
| Autumn | 124 | 118 |

Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 11-5). To compare this table with the data from Table 11-3 and 11-4, the "excluding weather" values should be used. In Table 11-5 the data are presented as seasonal and annual 50th and 90th percentile standard visual range for Mesa Verde. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season. The estimated visual ranges and light extinction coefficients are similar for both the transmissometer measurements and the reconstructed values based on aerosol concentrations.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions. The measured extinction data are used to verify the calculated reconstructed extinction and can also be used to run plume and regional haze models and to analyze visibility trends and conditions. Because of the larger spatial and temporal range of the aerosol data, the use of the reconstructed extinction data are preferred.

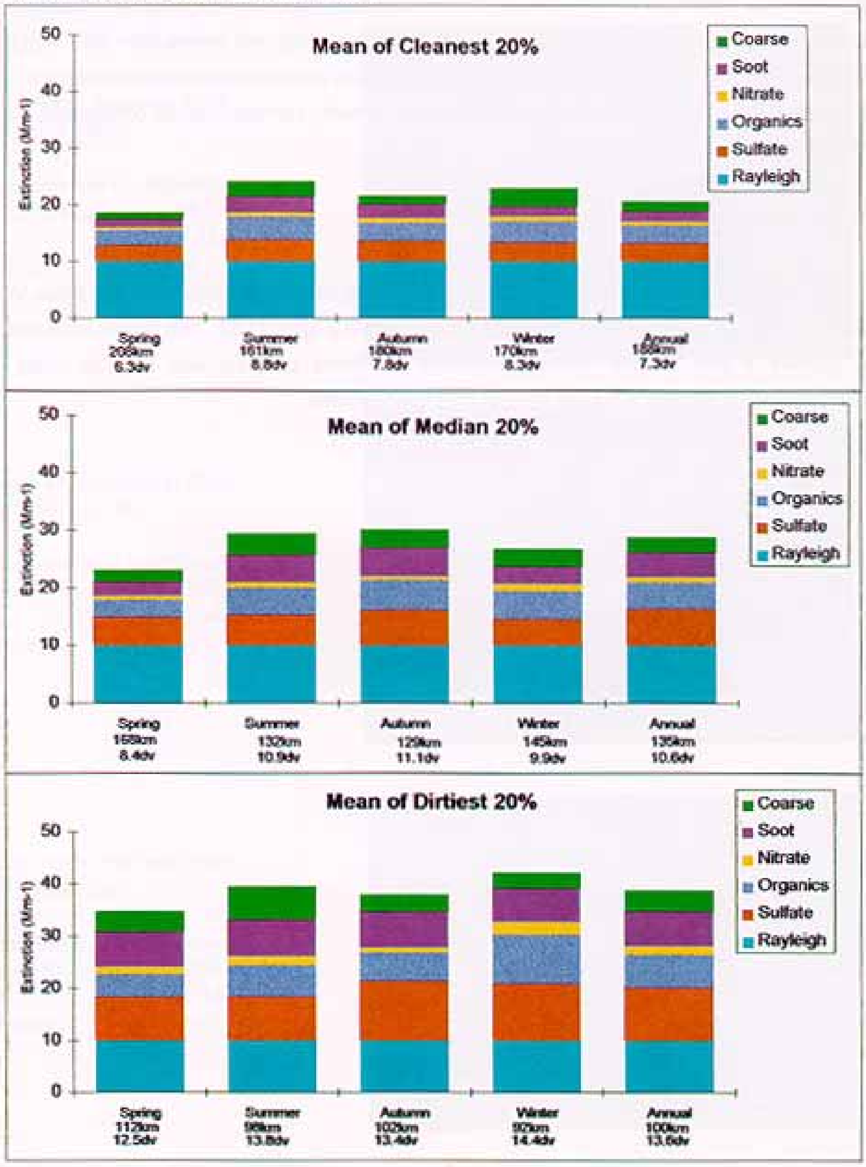
Table 11-5. Reconstructed visual range and light extinction coefficients for Mesa Verde National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentile by season, March 1988 - February 1994.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 136 | 28.7 | 194 | 20.2 |
| Spring | 148 | 26.3 | 199 | 19.6 |
| Summer | 128 | 30.4 | 144 | 27.2 |
| Autumn | 137 | 28.6 | 180 | 21.7 |
| Annual | 136 | 28.8 | 192 | 20.4 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Mesa Verde to specific aerosol species (Figure 11-4). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of days, mean of median 20% of days, and mean of dirtiest 20% of days. The "dirtiest" and "cleanest" signify highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicate cleaner conditions.

Figure 11-4. Reconstructed extinction budgets for Mesa Verde National Park, March 1993 through February 1994.

**Figure 11-4. Reconstructed extinction budgets for Mesa Verde NP, March 1993 through February 1994.**



Atmospheric light extinction at Mesa Verde National Park, like many rural western areas is largely due to sulfate, organic, and soot aerosols. In pre-industrial times, visibility would vary with patterns in weather, winds (and the effects of winds on coarse particles), and smoke from fires. We have no information on how the distribution of visibility conditions at present differs from the profile under “natural” conditions, but the cleanest 20% of the days probably approach natural conditions (GCVTC 1996).

### Photographs

Three photos are provided to represent the range of visibility conditions for the Mesa Verde National Park transmissometer cumulative frequency data (Figure 11-5). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what the observer sees.

Figure 11-5. Photographs representing visibility conditions at Mesa Verde National Park.

Figure 11-5. Photographs representing visibility conditions at Mesa Verde National Park.

**Mesa Verde National Park**
on a "clear" day.

Representative Conditions:
Visual Range: 340 - 391 km
$b_{ext}$: 12 - 10 $Mm^{-1}$
Haziness: 1 - 0 dv

**Mesa Verde National Park**
on a "average" day.

Representative Conditions:
Visual Range: 250 - 300 km
$b_{ext}$: 16 - 13 $Mm^{-1}$
Haziness: 4 - 3 dv

**Mesa Verde National Park**
on a "dirty" day.

Representative Conditions:
Visual Range: 180 - 220 km
$b_{ext}$: 22 - 18 $Mm^{-1}$
Haziness: 8 - 6 dv

## Visibility Projections

The Grand Canyon Visibility Transport Commission (GCVTC 1996) projected likely visibility for Mesa Verde through 2040, and the major species responsible for visibility impairment (Figures 11-6, 11-7). Reduced emissions from utilities were projected to reduce light extinction by approximately 1 $Mm^{-1}$. Light extinction caused by vehicle emissions was projected to decline until approximately 2005, and then increase through 2040. The dirtiest days have more than twice the visibility impairment than the cleanest days, and the bulk of the change results from human-related sources.

Figure 11-6. Projected “baseline” light extinction for Mesa Verde National Park (GCVTC 1996).

Figure 11-6. Projected "baseline" light extinction for Mesa Verde National Park (GCVTC 1996).

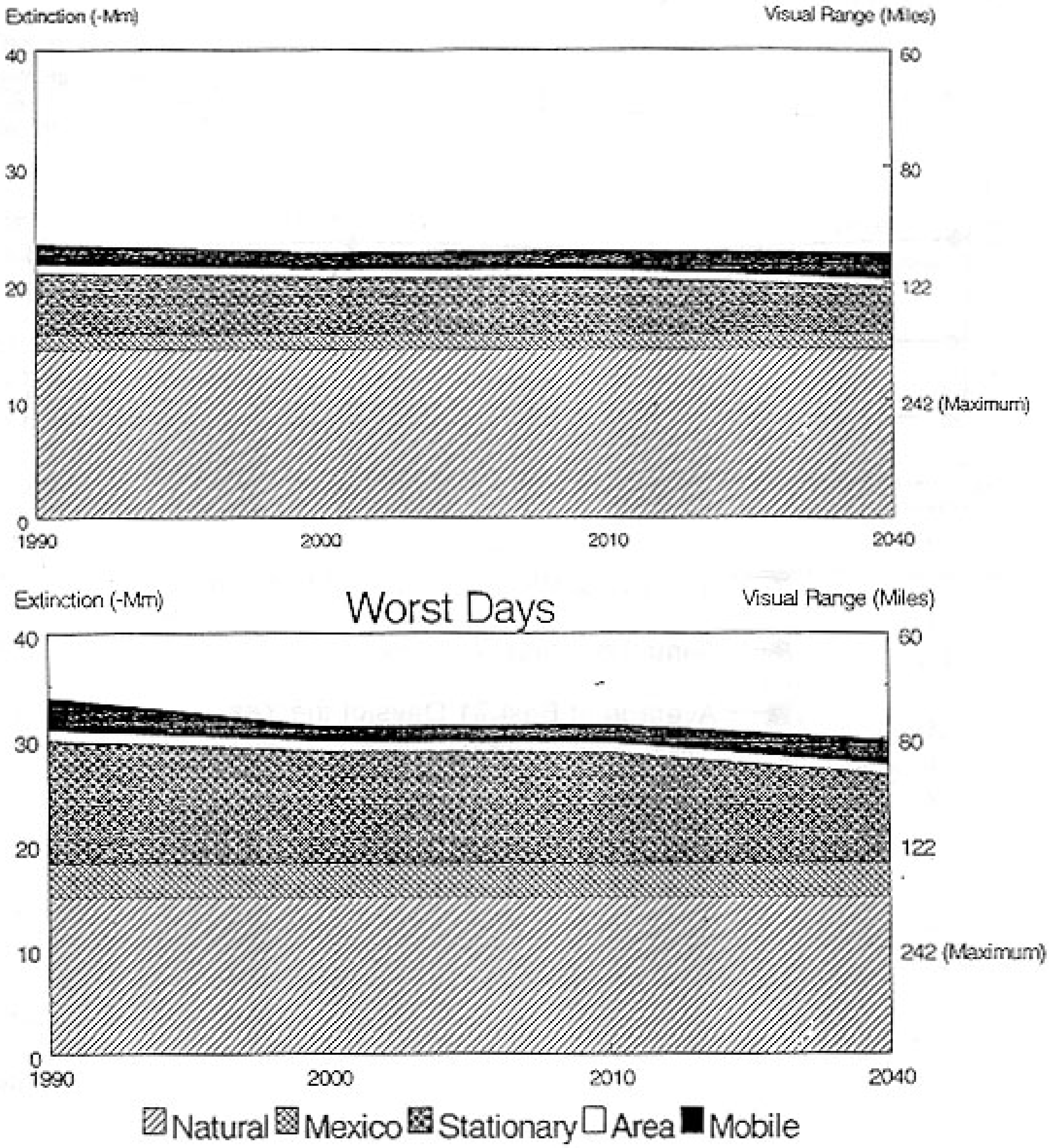


Figure 11-7. Projected “baseline” visibility for Mesa Verde National Park for good, average, and poor visibility conditions (GCVTC 1996).

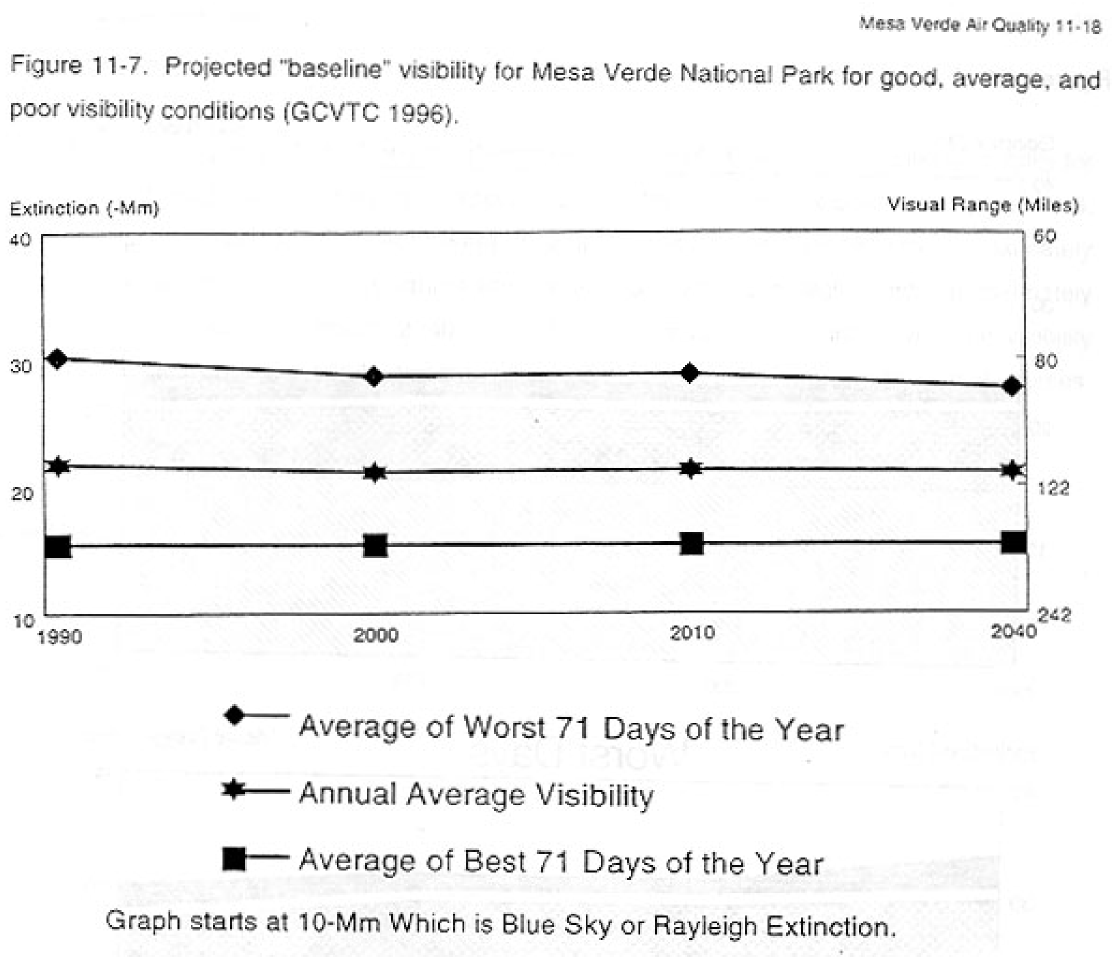


Figure 11-7. Projected "baseline" visibility for Mesa Verde National Park for good, average, and poor visibility conditions (GCVTC 1996).

Graph starts at 10-Mm Which is Blue Sky or Rayleigh Extinction.

*Atmospheric Deposition*

The rates of atmospheric deposition for Mesa Verde National Park are relatively low (Table 11-6). Precipitation pH averages about 4.9. Deposition of N averages about 1.5 kg N $ha^{-1}$ $yr^{-1}$, and S deposition averages about 2 kg S $ha^{-1}$ $yr^{-1}$. No trend is apparent for the concentration or deposition of N, but S deposition declined by an average of 8 mg S $m^{-2}$ $yr^{-1}$ (0.08 kg S $ha^{-1}$ $yr^{-1}$; $r^2 = 0.5$, $p < 0.01$; see also Lynch et al. 1996). There is no evidence that such low levels of deposition pose any threat to plants (see Chapter 2), and recent assessments indicate no risk for archeological sites (Petuskey et al. 1995).

Table 11-6. Atmospheric deposition for Mesa Verde National Park (NADP). Note the values for N and S compounds include the whole molecule and not just the N or S atoms.

| | Concentrations (mg/L) | | | Deposition (kg ha$^{-1}$ yr$^{-1}$) | | | | Conductivity (μS/mm) | Precipitation (mm/yr) |
|---|---|---|---|---|---|---|---|---|---|
| year | $NH_4$ | $NO_3$ | $SO_4$ | $NH_4$ | $NO_3$ | $SO_4$ | pH | | |
| 1981 | 0.15 | 1.30 | 2.14 | 0.46 | 3.95 | 6.51 | 4.73 | 1.89 | 304 |
| 1982 | 0.13 | 0.89 | 1.43 | 0.84 | 5.78 | 9.29 | 4.69 | 1.40 | 649 |
| 1983 | 0.09 | 0.70 | 0.96 | 0.52 | 4.01 | 5.50 | 4.88 | 0.95 | 573 |
| 1984 | 0.17 | 1.23 | 1.51 | 0.69 | 5.02 | 6.17 | 4.75 | 1.57 | 408 |
| 1985 | 0.07 | 0.72 | 1.07 | 0.37 | 3.85 | 5.72 | 4.91 | 1.01 | 535 |
| 1986 | 0.09 | 0.72 | 0.95 | 0.58 | 4.61 | 6.08 | 4.89 | 0.96 | 640 |
| 1987 | 0.13 | 0.94 | 1.08 | 0.63 | 4.57 | 5.25 | 4.80 | 1.09 | 486 |
| 1988 | 0.07 | 1.04 | 1.14 | 0.29 | 4.26 | 4.67 | 4.82 | 1.23 | 410 |
| 1989 | 0.21 | 1.29 | 1.20 | 0.56 | 3.41 | 3.17 | 4.96 | 1.15 | 265 |
| 1990 | 0.18 | 1.20 | 1.31 | 0.77 | 5.12 | 5.59 | 4.87 | 1.39 | 427 |
| 1991 | 0.10 | 0.88 | 1.01 | 0.49 | 4.36 | 5.00 | 4.86 | 1.10 | 495 |
| 1992 | 0.17 | 0.87 | 0.90 | 0.85 | 4.34 | 4.49 | 4.94 | 0.89 | 498 |
| 1993 | 0.11 | 0.74 | 0.77 | 0.58 | 3.88 | 4.03 | 5.02 | 0.76 | 524 |
| 1994 | 0.15 | 1.10 | 1.02 | 0.69 | 5.08 | 4.71 | 4.80 | 1.15 | 462 |

## Sensitivity of Plants

No signs of injury signs from air pollution have been reported for vegetation in or near Mesa Verde National Park. Only a few of the Park's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants (such as aspen), we expect that current ozone exposures could be high enough to affect some species. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Water Quality and Aquatic Organisms

Mesa Verde National Park is situated on a sandstone plateau with deeply cut drainages that flow into the Mancos River, which forms part of the eastern boundary of the Park. Surface water bodies are few and mainly ephemeral in nature. This hydrogeological setting and potential buffering by soils and sediments are similar to many of the other park units on the Colorado Plateau; therefore we would expect that surface water bodies have high ANCs. We were not able to locate any surface water chemistry data for the Park.

### *Amphibians*

Although we could locate few aquatic system data from Mesa Verde National Park, there is a published species list for amphibians found in the park (Douglas 1966): Utah tiger salamander (*Ambystoma tigrinum utahense*), Red-spotted toad (*Bufo punctatus*), Rocky Mountain toad *(Bufo woodhousei woodhousei*), and the Western leopard frog (*Rana pipiens brachycepala*). There is no evidence of sensitivity of amphibians to atmospheric deposition at rates experienced in Mesa Verde.

## Recommendations for Future Monitoring and Research

General recommendations for Class I NPS areas of the Colorado Plateau are provided in Chapter 14, and many of these apply to Mesa Verde National Park. Air quality monitoring at Mesa Verde includes continuous monitoring of ozone, IMPROVE sampler, and sampling of atmospheric deposition (NADP). We have no recommendations for additional monitoring of air quality.

No water quality data are available for the Park. We do not recommend that these data be collected unless Park staff are able to locate areas having both resistant bedrock geology and important habitat for vertebrate or invertebrate species. If such a situation is found, then we recommend reconnaissance monitoring for pH, ANC, sulfate, and nitrate in these waters.

## Park Summary

Visibility is currently the only AQRV known to be impacted by pollution at Mesa Verde, as with the other National Park Service Class I areas of the Colorado Plateau. Current levels of pollution in southwestern Colorado are high enough to produce haze and obscure the important vistas of the Park and surrounding areas. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Mesa Verde.

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

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# Chapter 12. Petrified Forest National Park

## Introduction

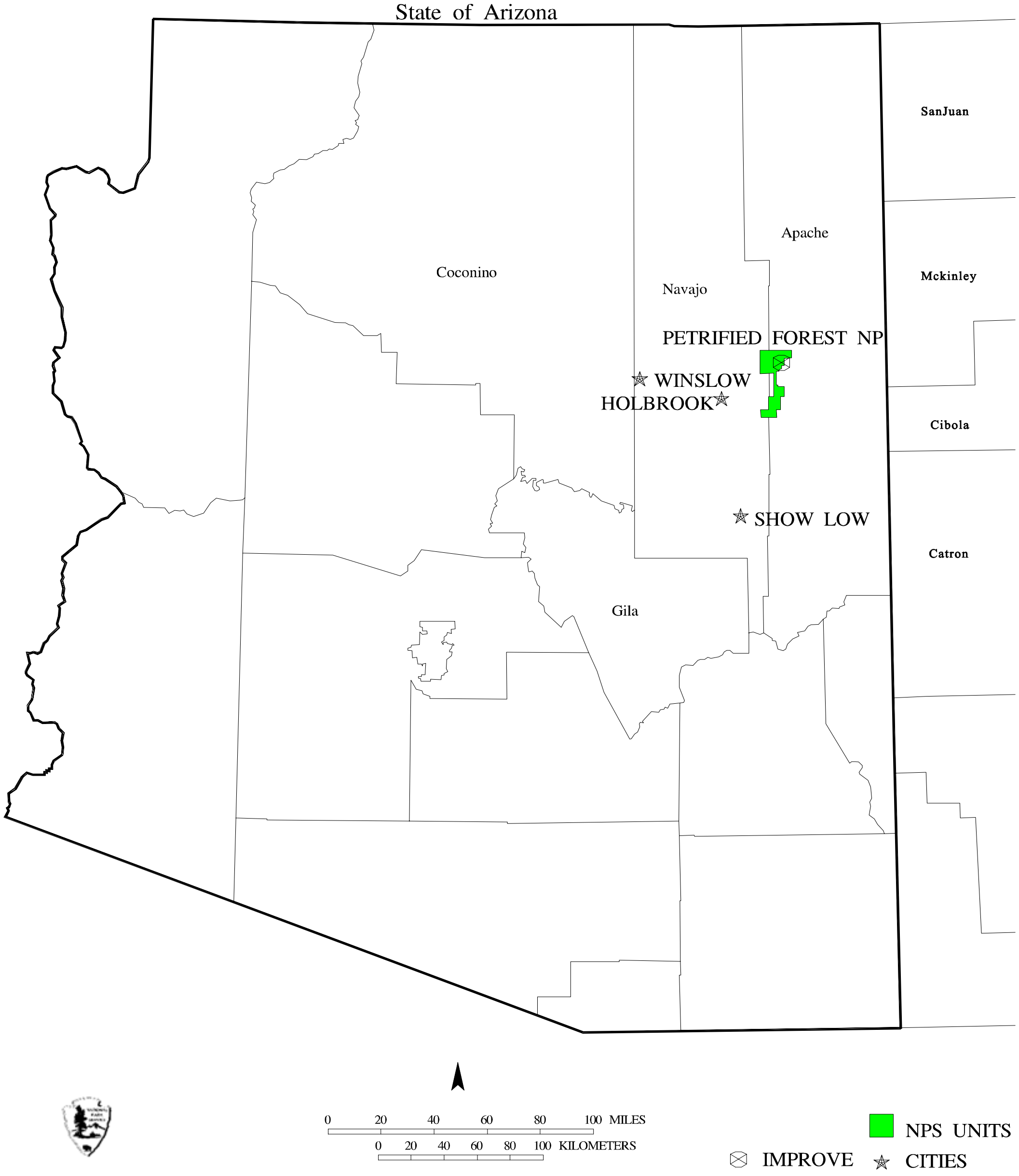
Petrified Forest National Park was established as a national monument in 1906 under the American Antiquities Act of 1906; the monument was converted to a national park in 1962. The Park is comprised of 37,900 ha (all federally owned), including about 20,000 ha of designated wilderness. The park was established to protect and preserve three primary features: petrified trees from the Triassic Period; various archeological ruins and petroglyphs; and portions of the colorful Painted Desert and associated badlands erosional formations. Petrified Forest National Park is located between 1600 and 1900 m in Apache County in northeastern Arizona on the southern end of the Colorado Plateau (Figure 12-1).

### *Geology and Soils*

The geology of Petrified Forest National Park began in the Triassic Period about 225 million years ago, when the region was an expansive floodplain that stretched from volcanic mountain ranges in south-central Arizona to low country in northern Arizona. Surrounding higher elevation areas were forested with primitive conifers. Over a period of millions of years, shorter periods of active volcanism killed these trees and they were toppled and sometimes transported downslope into the marshy floodplain. Once in the floodplain, they were quickly buried by layers of volcanic ash, sand, silt and clay. Conditions were favorable for silica from the water to slowly infiltrate plant cells, imbedding the organic material in silica crystals of beautiful colors that characterize the petrified wood of the Park and the region. The same processes that resulted in the burial of trees also resulted in the Chinle Formation, which is exposed today as the shales of the Painted Desert.

During the Cretaceous Period, seas advanced once again and thick shales and sandstone layers were laid down. About 70 million years ago the region began to uplift, the seas withdrew and erosional processes dominated the geologic development of the landscape. The Chinle Formation

Figure 12-1. Location of Petrified Forest National Park.



Map produced by the National Park Service Air Resources Division

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

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is comprised of mudstone and shale material that largely weathers into smectite clays with shrink swell properties (often called bentonite). These “badland” desert systems are sparsely vegetated because plants have great difficulty in establishing in the easily eroded, shrinking and swelling soils (Chronic 1988). A soil survey was conducted for Apache County that details the soils of the Park. There are roughly five main soil types broken down into various series, most of which have their origin in the Chinle Formation or younger sandstones of the later Mesozoic. Most soils are characterized by shallow development, high erosion, and low water permeability.

### *Climate*

The climate of Petrified Forest is semi-arid, receiving about 270 mm/yr of precipitation (Figure 12-2). Most of the rain falls during the winter and spring months, with a second peak during the mid-summer monsoons. Temperature are moderately high in the summer (averaging 24 $^{o}$C), and moderately cold in the winter (averaging -2 $^{o}$C). The winds in winter come from the west, southwest, and south, shifting to southeast and east in the summer and autumn (Figure 12-3).

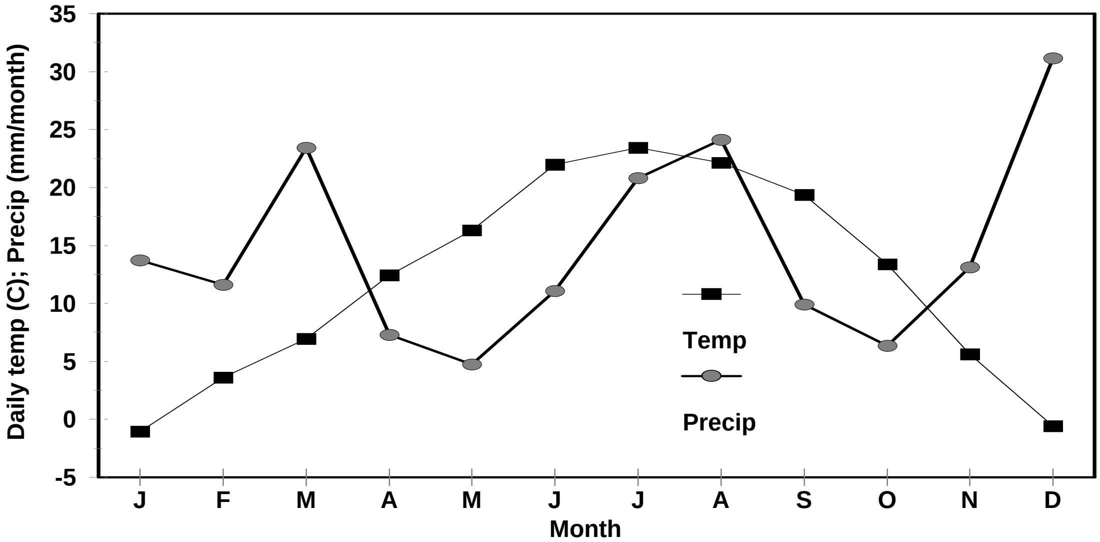
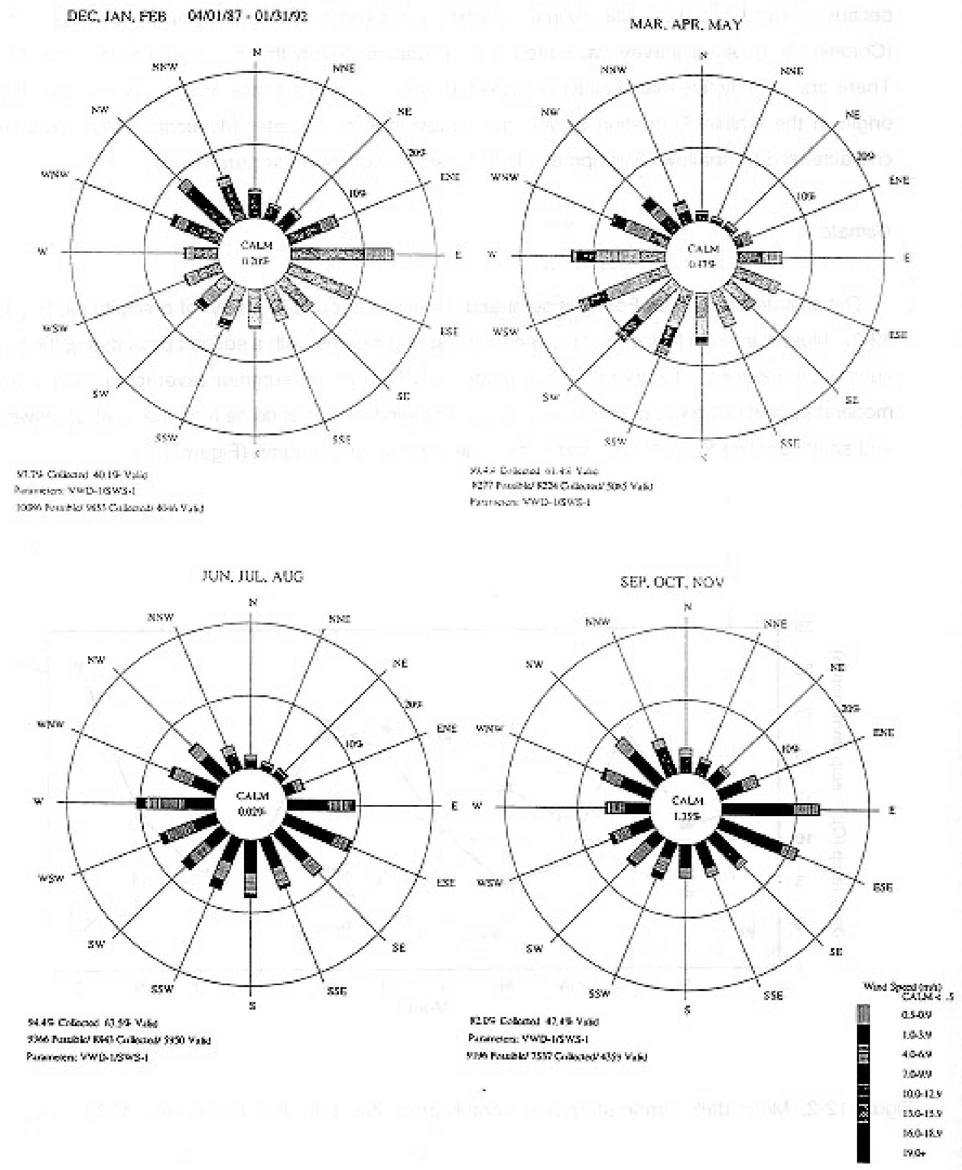


Figure 12-3. Seasonal wind roses for Petrified Forest National Park (1987-1992).

Figure 12-3. Seasonal wind roses for Petrified Forest National Park (1987-1992).



### *Vegetation*

The vegetation of Petrified Forest National Park is dominated by semi-desert grasslands, with some conifer woodland communities at the northern end of the park. The dominant grass species in the grasslands are *Bouteloua eriopoda*, *Pleuraphis jamesii*, and *Sporobolus* spp., with scattered rabbitbrush (*Chrysothamnus* spp.), saltbush (*Atriplex* spp.), sagebrush (*Artemisia* spp.), Mormon tea (*Ephedra* spp.) and juniper (*Juniperus monosperma*). In the woodland communities, juniper dominates with some pinyon pine (*Pinus edulis*) and other shrubs. There is currently little information about the distribution and abundance of plant species across the Park and no vegetation monitoring program is in place to document the current distribution and abundance and potential future changes. No information is available on the distribution or abundance of exotic species. A listing of plant species is provided by NPFlora. The Park has one known endangered plant species: the cactus *Pediocactus peeblesianus* (Threatened and Endangered Species Information Institute 1993). Species of special concern to the NPS are *Astragalus xiphoides* and *Pediocactus papyracanthus*. No listing is available in NPLichen for the Park, but a survey was done by a graduate student (Davis 1992).

## Air Quality

Air quality monitoring for Petrified Forest National Park consists of ozone data from 1987-1991, sulfur dioxide measurements for 1988, and IMPROVE monitoring for visibility from 1988 to the present (from Jasper Forest to Blue Mesa for transmissometer; from 1 km northeast of park headquarters for the camera; at park headquarters for the particulate sampler). No NADP site is close enough for direct use in estimating deposition for Petrified Forest.

### *Emissions*

Table 12-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 8 counties surrounding Petrified Forest. Many large point-sources of $SO_x$ occur in these counties, including: two Salt River Project stations (in Coconino and Apache Counties) , and two Arizona Public Service power stations (in Navajo County, Arizona, and San Juan County, New Mexico). No information is available to relate these emissions to air quality at Petrified Forest, or to apportion Petrified Forest’s air quality impairment to local and regional sources.

Table 12-1. Emissions (tons/day) for counties surrounding Petrified Forest National Park (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Apache, AZ | 139 | 3.2 | 83 | 118 | 554 | 64 |
| Coconino, AZ | 146 | 3.2 | 133 | 209 | 659 | 213 |
| Gila, AZ | 71 | 1.2 | 13 | 79 | 246 | 93 |
| Navajo, AZ | 167 | 2.7 | 79 | 83 | 559 | 68 |
| Catron, NM | 12 | 1.6 | 1 | 83 | 170 | 0 |
| Cibola, NM | 6 | 0.1 | 4 | -- | 199 | 2 |
| McKinley, NM | 151 | 2.2 | 41 | 47 | 320 | 8 |
| San Juan, NM | 167 | 1.2 | 197 | 50 | 372 | 176 |

### *Air Pollutant Concentrations*

The average concentrations of ozone in 1987-1991 were low, about 40 ppb (Table 12-2). However, Petrified Forest consistently had higher peak concentrations (from 97 to 134 ppb for 1-hr maximum) than any of the Parks or Monuments on the Colorado Plateau. The average concentrations are too low to cause any impact on sensitive species, but the peak concentrations are into the middle range of concentrations that affect sensitive species, and cumulative exposures may be near the lower threshold for effects on sensitive species (see Chapter 2). No reports of injury or growth effects have been noted. The concentrations of $SO_2$ were far below any threshold of suggested sensitivity for any plants.

Table 12-2. Concentrations of ozone and $SO_2$ for Petrified Forest National Park between May and September. For ozone, upper value is mean daily concentration (ppb); middle number is the maximum 3-month Sum60 exposure (ppb-hr in excess of 60 ppb for 12 hr/day); and bottom number is the maximum 1-hr concentration observed each year. $SO_2$ 24-hr averages by IMPROVE filter samplers (ppb) (1 $\mu g/m^3$ approximately equals 0.38 ppb). Ozone data from the NPS Air Resources Division's Quick Look Annual Summary Statistics Reports (provided by D. Joseph, NPS-ARD).

| Year | Ozone | $SO_2$ |
|---|---|---|
| 1987 | | |
| Mean | 42 | |
| Sum60 | 19056 | |
| Max | 116 | |
| 1988 | | |
| Mean | 39 | 0.2 |
| Sum60 | 6933 | |
| Max | 101 | 0.8 |
| 1989 | | |
| Mean | 43 | |
| Sum60 | 13496 | |
| Max | 104 | |
| 1990 | | |
| Mean | 40 | |
| Sum60 | 10362 | |
| Max | 97 | |
| 1991 | | |
| Mean | 41 | |
| Sum60 | 10776 | |
| Max | 134 | |

### *Visibility*

Visual air quality was monitored using a transmissometer, aerosol sampler and a camera. Petrified Forest National Park is part of the IMPROVE Monitoring Network. The transmissometer began operation in April 1987, the aerosol sampler began operation in March 1988, and the camera operated from July 1986 through April 1995. The data from this IMPROVE site have been summarized to characterize the full range of visibility conditions for April 1987 through February 1994, based on seasons of spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February).

#### Optical Data - Transmissometer

The transmissometer system consists of two individually-housed primary components: a transmitter (light source) and a receiver (detector). The atmospheric extinction coefficient ($b_{ext}$) at any time can be calculated based on the intensity of light emitted from the source and that measured by the receiver (along with the path length between the two). Transmissometers provide continuous, hourly $b_{ext}$ measurements. Weather factors such as clouds and rain can affect transmissometer measurements, but these can be "filtered out" by removing data points with high relative humidities (RH>90%).

The data are presented by season and annual median values, with and without meteorological factors in Table 12-3. The data are presented in units of extinction coefficient in $Mm^{-1}$ and standard visual range in km. Extinction coefficients represent the ability of the atmosphere to scatter and absorb light. Median values with large differences between the extinction values "including weather" and "excluding weather" indicate periods dominated by precipitation. Higher extinction coefficients signify lower visibility. Similarly, season and annual medians with nearly equal "including weather" and "excluding weather" extinctions indicate visibility reduction caused principally by particles. Visibility tends to be worst in the summer (Table 12-4).

Table 12-3. Transmissometer data summary for Petrified Forest National Park for 1987-1994. (SVR = standard visual range; $b_{ext}$ = light extinction coefficient.)

| Season Year | Excluding Weather | | Including Weather | |
|---|---|---|---|---|
| | SVR (km) | $b_{ext}$ (Mm$^{-1}$) | SVR (km) | $b_{ext}$ (Mm$^{-1}$) |
| Spring 1987 | 139 | 28 | 134 | 29 |
| Summer | 125 | 31 | 121 | 32 |
| Autumn 1987 | 162 | 24 | 144 | 27 |
| Annual 1987 | 140 | 28 | 135 | 29 |
| Winter 1988 | 227 | 17 | 194 | 20 |
| Spring 1988 | 169 | 23 | 162 | 24 |
| Summer | 134 | 29 | 130 | 30 |
| Autumn 1988 | 139 | 28 | 130 | 30 |
| Annual 1988 | 149 | 26 | 139 | 28 |
| Winter 1989 | 194 | 20 | 176 | 22 |
| Spring 1989 | 121 | 32 | 121 | 32 |
| Summer | 102 | 38 | 97 | 40 |
| Autumn 1989 | 139 | 28 | 134 | 29 |
| Annual 1989 | 130 | 30 | 125 | 31 |
| Winter 1990 | 149 | 26 | 144 | 27 |
| Spring 1990 | 149 | 26 | 149 | 26 |
| Summer | 134 | 29 | 130 | 30 |
| Autumn 1990 | 130 | 30 | 121 | 32 |
| Annual 1990 | 139 | 28 | 134 | 29 |
| Winter 1991 | 121 | 32 | 114 | 34 |
| Spring 1991 | 111 | 35 | 111 | 35 |
| Summer | 114 | 34 | 111 | 35 |
| Autumn 1991 | 130 | 30 | 125 | 31 |
| Annual 1991 | 118 | 33 | 114 | 34 |
| Winter 1992 | 134 | 29 | 71 | 55 |
| Spring 1992 | 114 | 34 | 111 | 35 |
| Summer | 114 | 34 | 111 | 35 |
| Autumn 1992 | 125 | 31 | 121 | 32 |
| Annual 1992 | 118 | 33 | 111 | 35 |
| Winter 1993 | 134 | 29 | 114 | 34 |
| Spring 1993 | 121 | 32 | 118 | 33 |
| Summer | 125 | 31 | 121 | 32 |
| Autumn 1993 | 144 | 27 | 134 | 29 |
| Annual 1993 | 134 | 29 | 125 | 31 |
| Winter 1994 | 144 | 27 | 144 | 27 |
| Spring 1994 | 121 | 32 | 118 | 33 |
| Summer | 118 | 33 | 118 | 33 |
| Autumn 1994 | 155 | 25 | 149 | 26 |
| Annual 1994 | 134 | 29 | 130 | 30 |

Table 12-4. Standard visual range for Petrified Forest National Park. Seasonal averages for median standard visual range in km from April 1987 - November 1994.

| Season | Excluding Weather | Including Weather |
|---|---|---|
| Winter | 158 | 137 |
| Spring | 131 | 128 |
| Summer | 121 | 117 |
| Autumn | 140 | 132 |

Aerosol Data

Aerosol sampler data are used to reconstruct the atmospheric extinction coefficient from experimentally determined extinction efficiencies of certain species (Table 12-5). To compare this table with the data from Table 12-3 and 12-4, the "excluding weather" values should be used. In Table 12-5 the data are presented as seasonal and annual 50th and 90th percentile standard visual range for Petrified Forest. The 50th percentile means that visual range is this high or lower 50% of the time. This is an average 50th percentile for each season. The 90th percentile means that the visual range is this high or lower 90% of the time. This is an average 90th percentile for each season. The estimated visual ranges and light extinction coefficients are similar for both the transmissometer measurements and the reconstructed values based on aerosol concentrations.

The reconstructed extinction data are used as background conditions to run plume and regional haze models. These data are also used in the analysis of visibility trends and conditions. The measured extinction data are used to verify the calculated reconstructed extinction and can also be used to run plume and regional haze models and to analyze visibility trends and conditions. Because of the larger spatial and temporal range of the aerosol data, the use of the reconstructed extinction data are preferred.

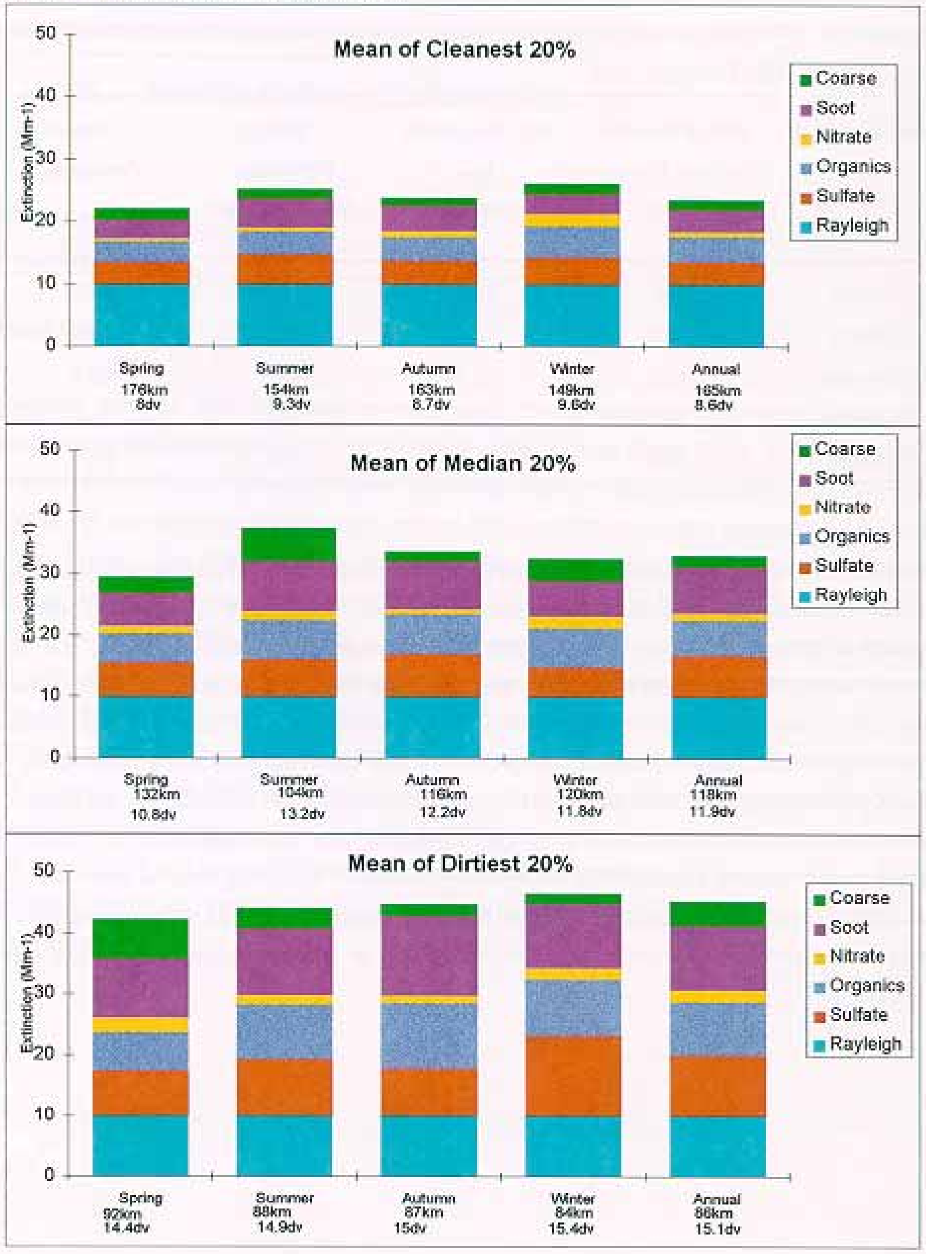
Table 12-5. Reconstructed visual range and light extinction coefficients for Petrified Forest National Park, based on IMPROVE aerosol sampler, seasonal and annual average 50th and 90th percentile by season, March 1988 - February 1994.

| Season/Annual | 50th Percentile Visual Range (km) | 50th Percentile $b_{ext}$ ($Mm^{-1}$) | 90th Percentile Visual Range (km) | 90th Percentile $b_{ext}$ ($Mm^{-1}$) |
|---|---|---|---|---|
| Winter | 105 | 37.1 | 161 | 24.3 |
| Spring | 120 | 32.6 | 157 | 24.9 |
| Summer | 102 | 38.2 | 131 | 29.9 |
| Autumn | 109 | 36.0 | 147 | 26.7 |
| Annual | 107 | 36.5 | 154 | 25.3 |

Reconstructed extinction budgets generated from aerosol sampler data apportion the extinction at Petrified Forest National Park to specific aerosol species (Figure 12-4). Visibility impairment is attributed to atmospheric gases (Rayleigh scattering), sulfate, nitrate, organics, soot, and coarse particles. The extinction budgets are listed by season and by mean of cleanest 20% of days, mean of median 20% of days, and mean of dirtiest 20% of days. The "dirtiest" and "cleanest" signify the days with the highest fine mass concentrations and lowest fine mass concentrations respectively, with "median" representing the 20% of days with fine mass concentrations in the middle of the distribution. Each budget includes the corresponding extinction coefficient, SVR, and haziness in dv. The sky blue segment at the bottom of each stacked bar represents Rayleigh scattering which is assumed to be a constant 10 $Mm^{-1}$ at all sites during all seasons. Rayleigh scattering is the natural scattering of light by atmospheric gases. Higher fractions of extinction due to Rayleigh scattering indicate cleaner conditions.

Figure 12-4. Reconstructed extinction budgets for Petrified Forest National Park, March 1993 through February 1994.

Figure 12-4. Reconstructed extinction budgets for Petrified Forest NP, March 1993 through February 1994.

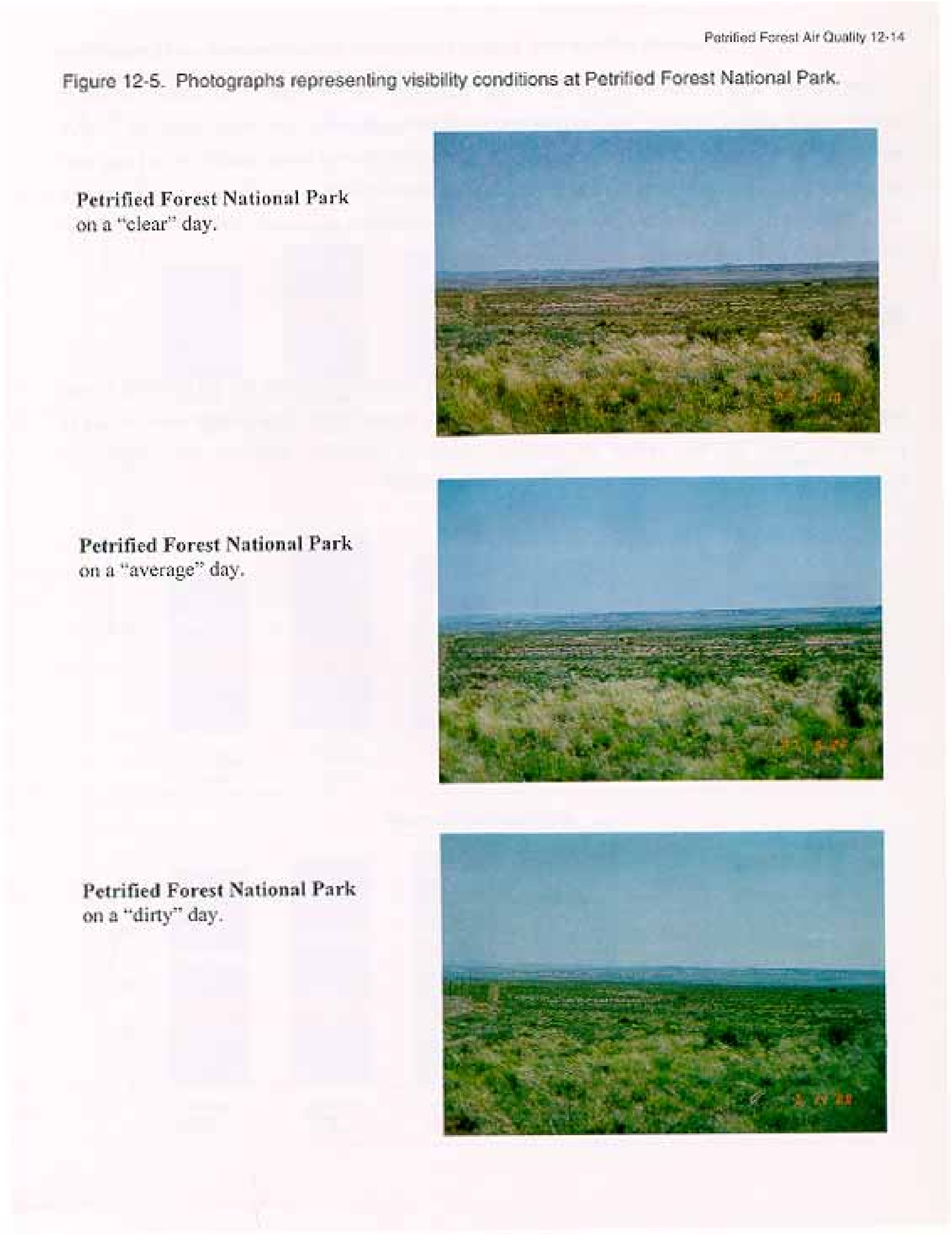


Atmospheric light extinction at Petrified Forest National Park, like many rural western areas, is largely due to sulfate, organic, and soot aerosols. Sulfates, organics, and soot contribute roughly equally to extinction on dirty, median, and clean days. In pre-industrial times, visibility would vary with patterns in weather, winds (and the effects of winds on coarse particles), and smoke from fires. We have no information on how the distribution of visibility conditions at present differs from the profile under "natural" conditions.

## Photographs

Three photos are provided to represent the range of visibility conditions for the Petrified Forest National Park transmissometer cumulative frequency data (Figure 12-5). The photos were chosen to provide a feel for the range of visibility conditions possible and to help relate the SVR/extinction/haziness numbers to what the observer sees.

Figure 12-5. Photographs representing visibility conditions at Petrified Forest National Park.



Petrified Forest Air Quality 12-14

Figure 12-5. Photographs representing visibility conditions at Petrified Forest National Park.

**Petrified Forest National Park**
on a "clear" day.

**Petrified Forest National Park**
on a "average" day.

**Petrified Forest National Park**
on a "dirty" day.

## Atmospheric Deposition and Water Quality

No NADP site is close enough to Petrified Forest to provide good estimates for deposition; rates are probably similar to those across the region (which are low). No surface water bodies exist in the Park.

## Sensitivity of Plants

No signs of injury from air pollution damage have been reported for vegetation in or near Petrified Forest National Park. None of the Park's species have been tested under controlled conditions for sensitivity to pollutants. Based on the ozone concentrations required to affect very sensitive plants, we expect that current ozone exposures (both peak concentrations and cumulative exposure) could be high enough to affect some species. Given the arid climate at Petrified Forest, it is possible that actual doses of ozone received by plants are lower than atmospheric concentrations would suggest; closed stomates during dry periods may substantially reduce ozone effects on plants. Current levels of ozone are the highest for NPS Class I areas of the Colorado Plateau, so some type of screening of major species for sensitivity (using controlled fumigation experiments) may be warranted. Levels of $SO_2$ are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

## Recommendations for Future Monitoring and Research

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Petrified Forest National Park. Specific recommendations for this Park are:

- An NADP site should be established for monitoring atmospheric deposition. This region has the highest $SO_x$ emissions in the area, and very high ozone concentrations. No NADP sites are close enough to provide representative data for this Class I area. We do not expect deposition rates to pose any imminent risk for AQRVs, but this gap in monitoring is one of the most notable on the Colorado Plateau.
- Some form of ozone monitoring be reinstituted at Petrified Forest, as previous data show very high levels, and no other Colorado Plateau site is close enough to represent conditions at Petrified Forest.
- A variety of plant species from this Park should be included in the controlled ozone fumigation experiments (described in Chapter 14), as many species from this Park do not occur in other NPS

areas of the Colorado Plateau.

## Park Summary

Visibility is currently the only AQRV known to be impacted by pollution at Petrified Forest, as with the other National Park Service Class I areas of the Colorado Plateau. Current levels of pollution in northeastern Arizona are high enough to produce haze and obscure the important vistas of the Park and surrounding areas. The ability of visitors to see the subtle pastel colors of the Painted Desert may be particularly sensitive to changes in haziness. Any increase in aerosols will undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Petrified Forest.

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations are too low to affect plants.

## References

Chronic, H. 1988. Pages of Stone, Geology of Western National Parks & Monuments, 4: Grand Canyon and the Plateau Country. The Mountaineers, Seattle, Washington, 158 pp.

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# Chapter 13. Zion National Park

## Introduction

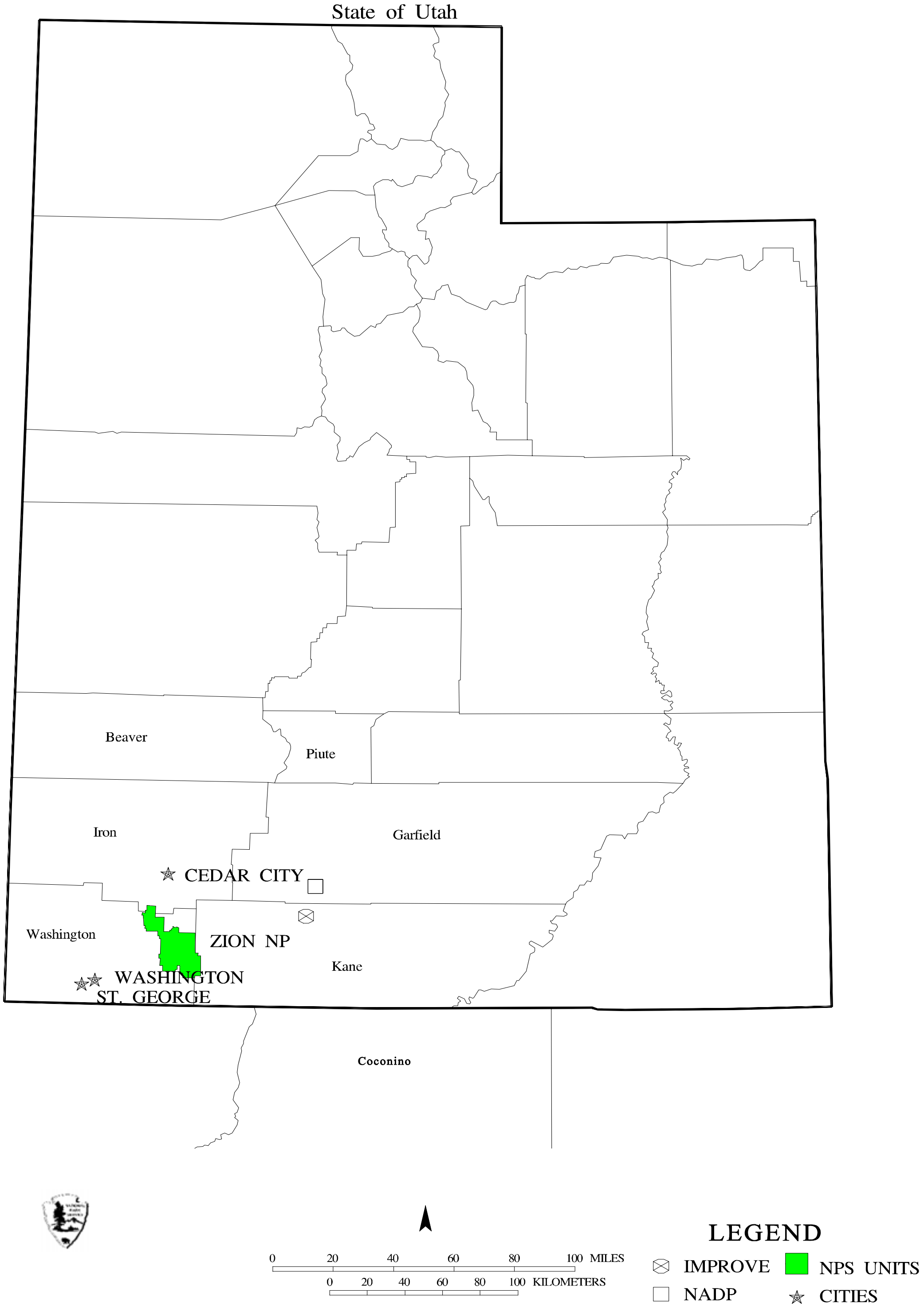
Zion National Park was established as Mukuntuweap National Monument in 1909 and then expanded and renamed as Zion National Monument in 1918 . Zion became a National Park in 1919. The purpose stated in the enabling legislation was to protect an extraordinary example of canyon erosion and features of unusual archeological, geological and geographic interest for scientific research, the enjoyment and enlightenment of the public, and visitor enjoyment of its grandeur and scenic features.

After a series of boundary changes, Zion National Park now encompasses 59,327 ha in the southwestern corner of Utah, of which 57,887 ha are federal. Zion National Park is on the far western edge of the Colorado Plateau and includes the southern and western perimeter of the Kolob Terrace which is a southern extension of the Markagunt Plateau (Figure 13-1). Zion Canyon is the main canyon in the Park and is the product of down-cutting of the Virgin River. This cutting has resulted in outstanding exposures of Triassic and Jurassic age deposits including 600 m thick sections of Navajo Sandstone. These exposures, along with the Kolob finger canyons to the north, and examples of quaternary volcanism to the west, are the main geological features of interest in the Park. Elevations range from 1117 m where the Virgin River leaves the Park to 2664 m at Horse Ranch Mountain in northern end of Zion. Many archeological sites are found in Zion. Most of the Park lies within Washington County, with a small eastern portion in Kane County and a small northern portion in Iron County. About 60% of Zion is bordered by BLM land, and the rest by private land.

### *Geology and Soils*

Most of the geology of Zion National Park begins in the Mesozoic era during the Triassic period, with only a small northwest tip of the park dating from the older Permian period. The Triassic was a dynamic time with climates that spanned equatorial wet climates to sub-tropical desert climates. During the 40 million years of the Triassic, tremendously varying depositional environments produced diverse strata, from the early Triassic silt and clay deposits of the dark red Moenkopi Formation to the mid-Triassic gravelly sandy Shinarump Conglomerate to the late Triassic, gray-blue

Figure 13-1. Location of Zion National Park.



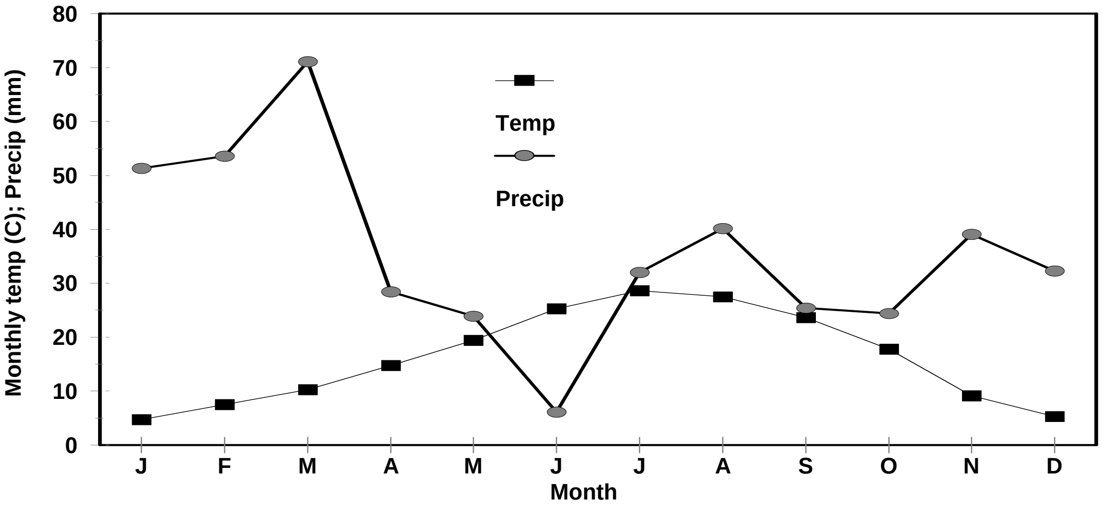
Map produced by the National Park Service Air Resources Division 12/19/96

Sources: USGS 1:2,000,000 cdrom and NPS ARD GIS

Chinle Formation formed from fine grained material derived from volcanoes. The entire region became a large desert of sand by the end of the Triassic and through the Jurassic; the sand dunes became the massive tan and red Navajo Sandstone. Seas advanced again at the end of the Jurassic, depositing the “cap” formations of Temple Cap Siltstone, topped by desert sand deposits of Carmel Sandstones. The youngest sedimentary layer in Zion is the Dakota Sandstone, a beach deposit at the edge of a Cretaceous sea. Near the end of the Cretaceous, the mountains to the east rose, forming the Rockies, and prevented any further incursions by seas. The subsequent Cenozoic Era has been a time of erosion in Zion National Park, including the down cutting through Mesozoic Era sediments by the Virgin River (Chronic 1988).

### *Climate*

The semi-arid climate of southwestern Utah is modified by Zion National Park’s intense topography and large elevation gradients. The higher elevation sites in the park are cooler and wetter while the opposite holds for lower elevation sites. At the park’s headquarters near Springdale, average daytime highs range from 11 $^{O}$C in January to 37 $^{O}$C in July, while night-time temperatures for these months average -2 $^{O}$C and 20 $^{O}$C (Figure 13-2). Most of the 370 mm of average annual precipitation falls as rain and snow from November to March, with a summer monsoon peak in July and August. June is particularly dry.



### *Vegetation*

Seven major vegetation types occur in Zion National Park (Harper 1994). Pinyon (*Pinus edulis*) / juniper (*Juniperus scopulorum*) is the most widespread community, covering over 46% of the Park. Rock Crevice communities and Great Basin Mountain shrubland communities, each cover about 13% of the Park, including some pinyon and juniper, Gambel oak (*Quercus gambelii*), serviceberry (*Amelanchier alnifolia*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), bigtooth maple (*Acer grandidentatum*) sagebrush (*Artemisia* spp.), and blackbrush *(Coleogyne ramosissima*). The ponderosa pine community type occurs over about 8% of the Park, and a mixed conifer community type dominated by Douglas-fir and white fir (*Abies concolor*) covers 6%. The remaining 14% of the Park is covered by barren rock, very arid Great Basin desert blackbrush and sagebrush shrublands, disturbed desert grasslands, and warm temperate riparian forests (with Fremont cottonwood (*Populus fremontii*)). A complete listing of plant species for Zion is provided by NPFlora while lichen lists for Zion are provided by Nash and Sigal (1981), NPLichen, and Rushforth et al. (1982). No information is available on threatened, endangered or rare plant species for Zion National Park.

Madany and West (1983) tried to gauge the legacy of cattle grazing within the Park by comparing vegetation on previously grazed Horse Pasture Plateau with ungrazed Church Mesa and Greatheart Mesa. These areas are dominated by ponderosa pine, and the ungrazed locations had higher densities of pine, oak and juniper saplings, and greater cover of grass and forb species. The authors attribute the differences in vegetation among these areas to grazing. The formerly grazed site had a much higher fire frequency (average return interval of 4 to 7 yr) prior to initiation of grazing in the 1880s than the ungrazed mesa (average return interval of 69 yr), which may indicate substantial differences in vegetation that relate more to fires than to grazing.

## **Air Quality**

### *Emissions*

Table 13-1 provides summaries for emissions of carbon monoxide (CO), ammonia ($NH_3$), nitrogen oxides ($NO_x$), volatile organic compounds (VOC), particulate matter (PM), and sulfur oxides ($SO_x$) for 7 counties surrounding Zion National Park. The emissions are relatively low, with the exception of Coconino County in Arizona where the Salt River Project’s Navajo Station is a major point source of $SO_x$. No information is available to relate these emissions to air quality at Zion National Park, or to apportion Zion's air quality impairment to local vs. regional sources.

Table 13-1. Emissions (tons/day) for counties surrounding Zion National Park (Radian 1994).

| County | CO | $NH_3$ | $NO_x$ | VOC | PM | $SO_x$ |
|---|---|---|---|---|---|---|
| Beaver, UT | 14.9 | 0.7 | 1.7 | 30.9 | 142.2 | 0.3 |
| Garfield, UT | 13.7 | 0.6 | 1.5 | 63.0 | 252.6 | 0.2 |
| Iron, UT | 36.1 | 0.9 | 3.7 | 38.8 | 190.0 | 0.9 |
| Kane, UT | 14.9 | 0.3 | 1.6 | 44.0 | 114.4 | 0.2 |
| Piute, UT | 4.6 | 0.4 | 0.5 | 8.9 | 8.1 | 0.1 |
| Washington, UT | 63.7 | 0.6 | 6.5 | 34.1 | 189.1 | 0.9 |
| Coconino, AZ | 145.5 | 3.2 | 132.8 | 208.7 | 658.6 | 213.2 |

### *Air Pollutant Concentrations, Visibility, and Atmospheric Deposition*

Almost no information is available for air quality in Zion National Park. Ozone concentrations in 1995 averaged 45 ppb, with a peak weekly concentration of 55 ppb, based on a passive ozone sampler. No information is available on visibility or atmospheric deposition, but regional patterns (such as those at Bryce Canyon and Grand Canyon National Parks) probably bracket the conditions at Zion. Subjective estimates of visibility were undertaken from 1975 to 1977, but discontinued because of lack of quantifiability (Zion National Park 1994). From 1977 through 1982, multi-day impactors were used to collect particulates; these data indicated good air quality, with particulates dominated by silicates. Teleradiometer readings were taken to gauge visibility between 1979 and 1986. Two solar-powered teleradiometers were installed with satellite data transmission, and 5 years of data were collected, but these data were not analyzed because the instrumentation has been discontinued. Transmissometer data represent visibility conditions better. A camera system was installed in the Taylor Creek area of the Kolob Canyon, and removed in 1991.

## Sensitivity of plants

No signs of air pollution injury have been reported for vegetation in or near Zion National Park. Only a few of the Park's species have been tested under controlled conditions for sensitivity to pollutants, and none of these tests included genotypes representative of the plants in the Park. Based on the ozone concentrations required to affect very sensitive plants, we expect that current ozone exposures could be high enough to affect some species. Unfortunately, too few data on ozone concentrations are available for a clear characterization of plant exposures. Current levels of ozone are probably too low to affect the conifers, and levels of $SO_2$ across the Colorado Plateau are far below any demonstrated threshold of sensitivity for any plants. In the absence of empirical evidence of any effects, no substantial problem is likely.

At least 160 species of lichen have been identified in Zion (Zion National Park 1994), and permanent transects have been established in the main Zion Canyon for long-term monitoring. No evidence of any pollution impact has been noted.

Johnson (1994) examined concentrations of zinc, manganese, lead, and cadmium in plants and soils adjacent to roads (within 30 m) and beyond (1000 m). He concluded that zinc, manganese and lead showed higher concentrations near the roads, but that levels were too low to pose a threat to plants, animals, or human health.

## Water Quality and Aquatic Organisms

The major water resource in Zion National Park is the Virgin River, cutting through the Zion Narrows. The Virgin River has substantial acid buffering capacity and is unlikely to be affected by acid deposition. The Park also has important freshwater habitats including springs, seeps, creeks and ponds that are relatively undisturbed, and which provide habitat islands for aquatic insects. The southeast side of the Park contains exposed bedrock, with rain-filled depressions called waterpockets, potholes or tinajas. These small water bodies vary in depth from several cm to 5 m, and are usually ephemeral. Gladney et al. (1993) measured ANCs as low as 220 ueq/l in potholes in Utah, indicating a moderately high buffering capacity of some of these water bodies. However, this lower bound of ANC is still not at the concern level for effects of acid deposition; water quality monitoring would be needed to determine the seasonal fluctuations in pothole chemistry. Given the similarity of geology between Zion and Capitol Reef National Park (Chapter 8), we expect that the aquatic systems are similarly well-buffered with respect to acid deposition.

### *Aquatic Invertebrates*

The pothole systems in Zion contain a number of aquatic organisms, including algae, zooplankton, water beetles (Hydrophyllids), backswimmers (Notonectids), dipteran larvae and amphibian larvae. Several unique species of aquatic insects have been recorded in the park in these refugia (Edmunds 1988): *Leptohyphes apache* (Order Ephemeroptera - found in the Virgin River); *Pteronarcys californica* and *Pteronarcys badia* (Order Plecoptera - Rocky Mountain species at their southern extent); *Ochrothrichia zioni* (Order Trichoptera - a rare endemic found in seeps in the park); *Hygrotus virgo* (Order Coleoptera - diving beetle endemic to SW Utah). It is unlikely that these invertebrates will be affected by deposition of acidic materials unless the rainfall pH dropped sufficiently for the pothole pHs to drop below 4.5 (Graham 1991).

## **Recommendations for Future Monitoring and Research**

General recommendations for NPS Class I areas of the Colorado Plateau are presented in Chapter 14, and many of these apply to Zion National Park. Our specific recommendations for this Park include:

- Instituting an air-quality monitoring program that includes at least passive ozone monitoring, and perhaps an NADP site. The IMPROVE network may not need an additional site at Zion to meet the program's regional goals, but the Class I designation of Zion National Park warrants visibility monitoring of some type. A passive ozone monitoring program would not provide estimates of peak concentrations, but may be adequate for estimating cumulative exposures.
- Zion National Park has many unique and important aquatic habitats that serve as refugia for vertebrates and invertebrates. The few measurements taken in pothole systems indicate that ANCs for some approach the level of concern (ANC less than 200 μeq/L). Presumably the water samples were taken during a static period, not following a rain storm or during the snowmelt runoff period. For these reasons we recommend:
    (1) a limited number of pothole systems be selected for periodic water chemistry monitoring to determine the seasonal fluctuations in pH, ANC, anions and cations;
    (2) if reconnaissance monitoring show depressions in pH or ANC or spikes in nitrate or sulfate concentrations, then a regular monitoring program should be put in place; and

(3) if funds are available, dose/response experiments could be conducted on selected pothole systems either in the Park or on adjacent lands (see recommendations for Capitol Reef National Park).

## Park Summary

Little information is available for air quality and AQRVs in Zion National Park. We expect that visibility is currently the only AQRV known to be impacted by pollution at Zion, as with the other NPS Class I areas of the Colorado Plateau. Current levels of pollution in southern Utah are probably high enough to produce haze and obscure the important vistas of the Park and surrounding areas. Any increase in aerosols would undoubtedly impair visibility further; substantial reductions in aerosols would be needed to restore pristine conditions at Zion National Park.

Little information has been collected on air pollution effects on the Park's biota. No sign of air pollution impacts on plant or animal species has been reported; ozone concentrations are high enough that some impact is possible for sensitive plants, but $SO_2$ concentrations on the Colorado Plateau are too low to affect plants.

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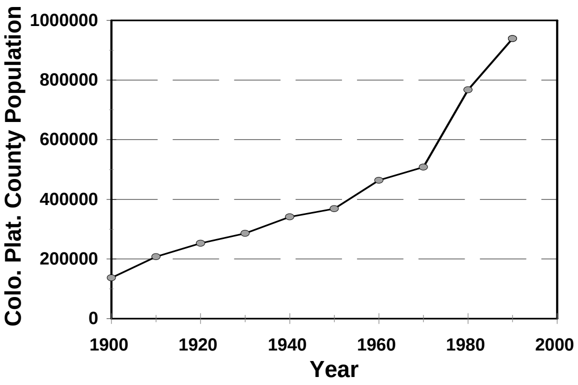
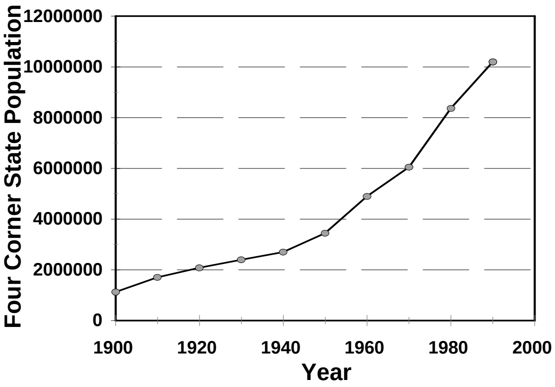
# Chapter 14. Colorado Plateau Summary and Recommendations

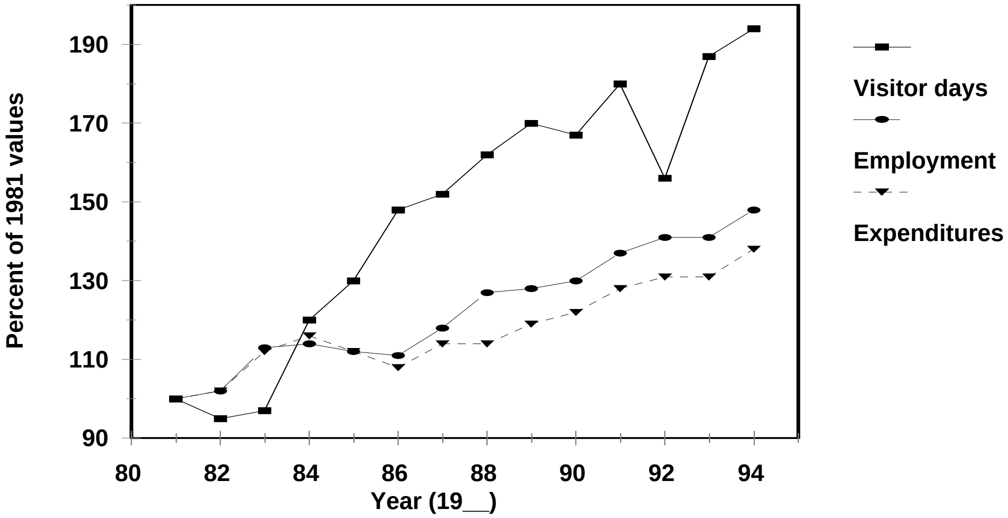
## Changes in the Colorado Plateau

Almost all aspects of the Colorado Plateau are experiencing substantial change. Human populations are increasing rapidly on the Colorado Plateau and in the Four-Corners states (Figures 14-1, 14-2). Visitation at the Grand Canyon is expected to reach 6 million visitors per year in the near future (GCVTC 1996). The vegetation in the National Parks and Monuments of the Colorado Plateau is currently undergoing substantial changes from a variety of causes. Fire suppression over the past 80 yrs has led to unusual accumulation of fuels, and to “outbreaks” of trees with forests replacing forest/grassland mixtures (Covington and Moore 1994). Many areas are also experiencing reduced or eliminated grazing by cattle. Prescribed fire programs in some Parks (such as Bryce Canyon) are designed to return vegetation to more natural composition and structure.





The growth in local and regional populations has been accompanied by very large increases in visitation to the National Park units of the Colorado Plateau (Figure 14-3). Visitation almost doubled between 1981 and 1994, from 8.7 million visitor days in 1981 to 16.7 million visitor days (Hecox and Ack 1995). The number of National Park Service employees increased at less than half of this rate, and expenditures (in constant 1981 dollars) lagged even further behind.



## Visibility

The protection of Air Quality Related Values (AQRVs) in the NPS Class I areas of the Colorado Plateau occurs in the context of many changes. Emissions of S compounds have generally declined around the region, but emissions of $NO_x$ compounds may remain constant and then increase in the next century (GCVTC 1996). Much of the increase in the next century will come from vehicle emissions, both within the region and from large population centers such as Phoenix, Salt Lake City, Las Vegas, and Los Angeles.

The major documented changes on AQRVs will be related to visibility. The Grand Canyon Visibility Transport Commission (GCVTC 1996) projected that visibility would improve for a few years, and decline again because reduced source emissions would be offset by an increase in sources as a result of economic activity and population. Natural production of aerosols in wildland fires has probably been abnormally low for several decades, but projected increases in prescribed fire and perhaps wildfire will periodically reduce visibility on the Plateau.

Reductions in visibility from sulfate may be marginally alleviated, depending on the degree to which emissions of $SO_2$ are reduced from existing sources or increased by additions of new point sources. Given that low-visibility days are due in large part to high concentrations of sulfate aerosols, any increase or decrease in S emissions should directly affect visibility. As identified by the GCVTC, there is an inability to differentiate local (Las Vegas, Nevada; Salt Lake City, Utah; Phoenix, Arizona) and regional sources of air pollution and their effects on visibility. Therefore, future studies could be focused on this issue.

## Air Pollutant Impacts on Vegetation

We found no evidence of any impact of current air quality conditions on other AQRVs such as vegetation or stream chemistry.

Ambient concentrations of $SO_2$ are far below thresholds for impacts on sensitive plants. Ozone concentrations are relatively low on an average basis, but moderate ozone exposures occur at certain periods in several of the Parks and Monuments. No evidence of any impacts (such as foliar injury or abnormal growth or mortality) has been reported. In general, the current levels of ozone are probably too low to affect the conifers, but may be high enough to affect aspen (and closely related cottonwoods?). Most shrubs, herbs, and grasses on the Plateau have never been screened for sensitivity to ozone.

## Sensitivity of Soils and Surface Waters to Acidification

In general, surface waters and watersheds of the Colorado Plateau are resistant to chemical change due to low levels of acidic deposition and to the nature of the region's hydrogeology. Some of the park units discussed in this review have some regions that are characterized by bedrock resistant to weathering (e.g. Great Sand Dunes National Monument). Small pools, ponds, and streams found on more crystalline rock may be susceptible to change due to atmospheric inputs. A potentially important data gap is the potential for aquatic system change due to nitrogen inputs to both the aquatic and terrestrial ecosystems of the Colorado Plateau.

The EPA recently issued a report that attempted to answer the question: "what acidic deposition levels are necessary to protect sensitive regions?" This study examined critical loads from the perspective of setting a standard that might have any one of the following environmental goals: a) maintenance of specific conditions as observed at a particular point in time, b) return to pre-industrial conditions, or c) a level that balances effects, costs, and other societal values (EPA 1995). The current pH of rainfall in the Plateau is not low enough to cause any direct acidification problems. Wet deposition of N is very low (about 1 kg N $ha^{-1}$ $yr^{-1}$ across the Plateau), and it is unlikely that such low rates could increase N availability enough to substantially alter any plant communities. A range of “critical loads” cannot be determined at this point because high ANC in water bodies and low rates of deposition have not allowed any impacts to be discerned. We conclude that current rates of deposition probably exceed pre-industrial conditions (b above), but that no impacts on AQRVs are apparent (a above). The NADP monitoring data show significant declines in S deposition at some sites on the Plateau, and no trends in N deposition. Our present finding of no impact on AQRVs from deposition of S and N may not hold if deposition rates increase substantially; research that included experimental treatments with realistic rates of S and N addition would be needed to form a basis for establishing critical loads.

### Recommendations

Visibility is the major known AQRV affected by current air quality on the Colorado Plateau. Human-related emissions contribute most of the visibility impairment when visibility is poorest. The IMPROVE protocols are sufficient for gauging patterns in visibility, and in identifying the compounds responsible for visibility impairment. Our synthesis showed that visibility differs among the Parks and Monuments of the Plateau. Therefore, air quality at one location cannot in general be extrapolated simply from other sites because of differences in major sources of pollution, distances from sources, and weather patterns. In addition, the Grand Canyon Visibility Transport Commission (GCVTC 1996) stressed that local sources of pollution may substantially impair visibility when low-wind weather systems dominate.

> Recommendation #1: Visibility is an important AQRV of the Colorado Plateau. Present visibility on the Plateau is impaired by pollution and would be sensitive to changes in pollutant concentrations. The data collected from IMPROVE Protocol monitoring provide a means to establish present conditions and estimate spatial and temporal trends. These data also form the basis of analyses that can, in a general way, identify source regions responsible for impairment. Additional monitoring for specific units and resources for special studies may be desirable, and more work is needed to identify the contribution of specific point sources and of urban centers (particularly Las Vegas and urban centers in California) to visibility impairment.

The National Park Service has a policy and obligation to develop baseline inventories of the natural resources protected within the National Parks and Monuments (Stohlgren et al. 1995). Most parks have incomplete species lists, only partial geographic information on location of species and communities, and few have any monitoring program that would identify moderate changes in the state of health of ecosystems. The Inventory and Monitoring Program of the NPS aims to achieve these goals (Ruggiero et al. 1992).

Recommendation #2: Substantial changes in vegetation are likely to develop in the coming decades, as a result of natural succession processes, fire regimes (including suppression, prescribed fire, and wildfire), responses to grazing (or cessation of grazing), visitor impacts, impacts of changing wildlife populations, and from driving forces such as pollution and climate change. The role of pollution in these changes can only be determined by adequate characterization of the nature and extent of changes, coupled with experimental information to determine the likely causes of the changes. Therefore, we recommend that broad-based resource monitoring in the Parks and Monuments be given a high priority.

- A reconnaissance survey of all Class I NPS areas is needed to determine if foliar injury from ozone is occurring. Ozone concentrations in some Parks and Monuments are high enough that injury is plausible, but none has been reported. The lack of injury reports could indicate no effects, or a lack of a thorough reconnaissance by experts who can identify foliar injury. A single late-summer expedition would provide a foundation for determining the extent of any current problem and whether follow up surveys (in more depth) are warranted. This reconnaissance-level survey could be repeated after any summer with notably high ozone concentrations. Other surveys may be useful in the future if unexpectedly large changes in air quality develop. These might include monitoring changes in the extent of lichen cover on rocks.

Recommendation #3: Monitoring of effects of deposition (both wet and dry) on surface waters needs to be continued or expanded. No estimates of rates of dry deposition are currently available for the Colorado Plateau, so an attempt should be made to estimate dry deposition rates using both the National Dry Deposition Network (NDDN) data and particle concentration data collected as part of the IMPROVE network. This work would need to examine and improve the algorithms that are currently used to translate ambient concentrations of dry species to deposition loadings.

- Too little is known about the biogeochemistry of small ponds and rock pools to know if increasing deposition of N (or S) could alter these unique ecosystems. Therefore, biological properties and pH, ANC, sulfate-S, ammonium-N, and nitrate-N should be monitored, particularly for water bodies with ANC < 200 μeq/L and those on resistant bedrock (such as quartzite). Sulfur isotope analysis of waters could be used to estimate the contribution of different sources of sulfur (e.g. power plants, smelters) to increased acidity and sulfate in these freshwaters. A number of parks are involved in cooperative projects with the USGS-Water Resources Division as part of the National Water Quality Assessment Program (NAWQA). We recommend that the park staff review the surface water chemistry data with USGS researchers periodically to identify waters that might be sensitive to changes due to deposition.

- An experimental focus is needed on the episodic change in chemistry of sensitive water during large events. Sensitive systems are most likely to show changes in chemistry and biota following large rain storms that flush accumulated dry deposition in small pools and streams. Where appropriate, rainfall events could be monitored, and short term responses in stream or pool chemistry could be studied (using automatic sampling devices). Before reaching conclusions about the effect of chemical changes on biota, controlled dose/response experiments would be needed (using native vertebrate and invertebrate species). In conducting these experiments it is important to determine the range of natural variability in both the chemistry of these systems and the biological response to changes in both hydrology and chemistry.

As mentioned above, a key challenge in any ecological monitoring program is deducing the processes that generated any changes that were observed over time. If aspen declines as a component of the forests on the North Rim of the Grand Canyon, would it be likely that ozone played a role? A variety of experiments are needed to determine the likely sensitivity of Colorado Plateau species and ecosystems to air quality.

Recommendation #4: A series of strategic experiments should be developed to address the likely impact of reasonable exposures to air pollutants and deposition.

- A wide range of plant species needs to be screened in controlled fumigation experiments for sensitivity to ozone (in the range of 40 to 60 ppb average, with peak exposures of 100-120 ppb). These fumigations need to include manipulations of water supply (for at least a subset of the species) to examine the effects of moisture stress on reducing the ozone impacts on the plants. Another possible approach for examining potential impacts of current ozone levels would be testing plants on-site in charcoal-filtered air; open top chambers could be placed around established plants with and without filtered air treatments. Any increased growth in the filtered chambers would be consistent with an ozone-induced effect on growth.

- The pollutant of most concern relative to setting of critical loads is N because of the likely increase in the emissions of nitrogen oxides and ammonia due to human activities. Experimental additions of N are needed to a wide variety of ecosystems (from grasslands, shrublands and forests to potholes and streams) to provide a basis for insights about critical loads of N deposition in the Colorado Plateau (similar to experiments by Wedin and Tilman 1996, but with much lower application rates of < 2 g N $m^{-2}$ $yr^{-1}$). When experimental manipulations within Parks are not feasible, surrounding land managed by the USFS or BLM may provide suitable "surrogate" sites. A modeling component may be an important part of projects that attempt to identify critical loads for Colorado Plateau ecosystems (both terrestrial and aquatic).

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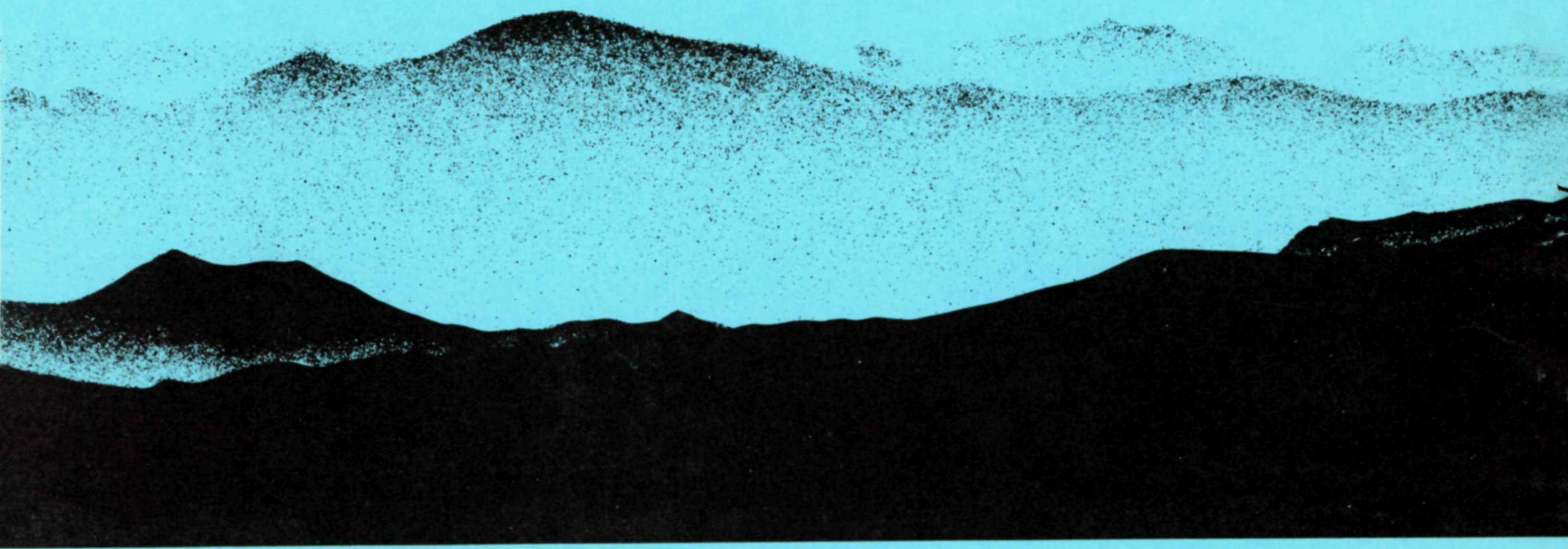

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