Protecting Wilderness Air Quality in the United States

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Abstract—Federal land managers are responsible for protecting air quality-related values (AQRVs) in parks and wilderness areas from air pollution damage or impairment. Few, if any, class 1 areas are unaffected by regional and global pollutants, such as visibility-reducing particles, ozone and deposition of sulfur (S), nitrogen (N) and toxics. This paper lays out the basic definitions and research findings that managers need to protect natural resources and scenic vistas. A detailed case study is presented that traces the development of scientific knowledge of the effects of S and N on wilderness resources. Gaps in our understanding of deposition and its effects, and managers' need for monitoring, modeling and data synthesis tools are discussed, with recommendations on how to use science and technology to protect AQRVs in wilderness areas and parks.

External threats to wilderness areas come in many forms. One of the most pervasive stresses is air pollution from local, regional and global emission sources. Federal land managers (FLMs) were initially concerned about the effects of local air pollution on surface waters, native vegetation, soils, wildlife and cultural resources. These threats included sulfur dioxide (SO_2), nitrogen oxides (NO_x), fluorides, lead (Pb) and soot from power plants, industries and urban areas. The United States has made considerable strides since the passage of the Clean Air Act in 1970 to clean up local sources of pollution. However, with the advent of "tall stacks" on large point sources, there is now more opportunity for long-distance transport of pollution to parks and wilderness areas. The greatest air pollution threat to natural resources and scenic vistas in remote wilderness areas currently is from regional and global pollutants.

The focus of this discussion will be on regional pollution issues: visibility, ozone and deposition of sulfur (S) and nitrogen (N) compounds (also known as "acid rain"). Other air pollutants of concern in wilderness areas will be defined, but not explored in any depth. The detailed case study of deposition includes information on (1) history of deposition research and monitoring, (2) what we know, (3) gaps in our knowledge, (4) how managers have used the data, (5) current needs of managers, and (6) research, monitoring and assessment strategies for FLMs.

Definitions and Overview

Basics of Class 1 Air Quality

Class 1 Areas—Wilderness areas over 5,000 acres in size, and national parks greater than 6,000 acres were singled out for special protection from air pollution under the Clean Air Act Amendments (CAAA) of 1977. There were 158 units in 1977 that received this level of protection. They are managed by the following Federal Land Managers (FLMs): USDA-Forest Service (USFS) (88 wilderness areas); DOI-National Park Service (NPS) (48 national parks and 1 international park); and DOI-U.S. Fish and Wildlife Service (FWS) (21 wilderness areas). Figure 1 shows the distribution of NPS protected areas. It is possible to add class 1 areas through a process known as redesignation. Five Native American lands that have been "redesignated" class 1.

Federal Land Managers—For the purposes of this discussion, the agencies that have stewardship over public lands designated as class 1 are known as federal land managers (FLMs). These include DOI-National Park Service, DOI-U.S. Fish and Wildlife Service, and USDA-Forest Service. FLMs that will not be specifically discussed in this paper are the DOI-Bureau of Land Management (BLM), which manages one class 1 wilderness area, and the Native American tribes, which can redesignate their lands as class 1. The three FLMs with the largest number of class 1 parks and wilderness areas have joined forces as part of the Federal Land Managers Air Quality-Related Values Work Group (FLAG), in an effort to coordinate activities in protecting air quality-related values (AQRVs) from air pollution. This group has recently issued a draft report that outlines the major air quality concerns and starts the process of setting thresholds and critical loads to protect sensitive resources (FLAG 1999).

Legal Responsibilities—The array of legislative requirements to protect parks and wilderness areas from air pollution are listed in the FLAG report (1999). These include the FLMs' Organic Acts, park and wilderness enabling legislation, Wilderness Act and Clean Air Act and its amendments. The National Environmental Policy Act requires that air quality be considered in environmental impact statements (EISs) for significant federal actions. Details of these mandates are included in Bunyak (1993).

Methods used by FLMs in an effort to control air pollution effects in class 1 areas include: (1) new source review of proposed air pollution sources within 100 km of the wilderness boundary, (2) request for Best Available Retrofit Technology (BART) to be installed on large power plants to remedy visibility impairment, (3) participation in regional air quality groups to implement the regional haze regulations (i.e., Western Regional Air Partnership), (4) providing

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Map produced by the National Park Service Air Resources Division 02/22/1999

Figure 1—National Park Service Class 1 areas.

research and monitoring data to the Environmental Protection Agency (EPA) in the review of National Ambient Air Quality Standards (NAAQS), (5) providing comments on environmental impact statements (EISs) for development that will affect class 1 areas, (6) providing data and comments on State Implementation Plans (SIPs), and (7) participation in bioregional assessments, such as the Sierra Nevada Ecosystem Project (SNEP) and the Southern Appalachian Mountains Initiative (SAMI 1999).

Criteria Air Pollutants—These air pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), particulate matter (PM-10) and lead (Pb) and were specifically identified by the EPA as harmful to human health and welfare. The EPA has set specific control levels for these pollutants, known as National Ambient Air Quality Standards (NAAQS), based on the concentrations in ambient air. For a discussion of current trends in these pollutants, see U.S. EPA (1998); and for a tutorial on urban air pollution, including its chemistry and physics, see Seinfeld (1989). In 1997, the EPA revised the NAAQS for ozone and introduced a new NAAQS for PM-2.5, fine particles less than 2.5 microns in diameter, known to affect human lung function, visibility and deposition of acidic materials. However, these new NAAQS were recently called into question in a court decision (May 1999); additional litigation will determine if they are reinstated.

The values for criteria air pollutants and NAAQS are based on protecting the sensitive people in the population. Sensitive scenic values and natural resources in parks and wilderness areas can be more sensitive to injury due to air pollution than the standards set by EPA (as in the case of ozone effects on sensitive tree species, such as Ponderosa pine (*Pinus ponderosa*) and black cherry (*Prunus serotina*)). Also, the form of the pollution that affects natural areas is often different from the form of the criteria pollutants. The major regional air pollutants discussed in this paper include: (1) fine particles (less than 2.5 microns), which affect visibility and scenic resources (Malm 1992), (2) ozone, which affects forest health (U.S. EPA 1996a; 1996b), and (3) deposition of sulfur and nitrogen, which has a myriad of effects: acidification of soils and freshwaters, eutrophication of estuaries and near-coastal marine systems and alteration of ecosystem processes and nutrient cycling by altering soil biogeochemistry (NAPAP 1998).

Regional Air Pollutants—Regional air pollutants that affect scenic and natural resources in class 1 areas include: fine particles, ozone, deposition of nitrogen and sulfur, and toxic air contaminants, especially mercury (Hg).

1. Fine particles: This class of pollutant is also known as visibility-reducing particles, or PM-2.5, and includes both primary and secondary particles with a diameter of less than 2.5 microns. The primary particles come from diesel exhaust, smelter emissions, forest fires and windblown dust. Secondary particles are the result of atmospheric transformations of SO_2, NO_x, ammonia (NH_3) and organic compounds. The chemical composition of the fine particles include, generally, sulfate and nitrate particles, organics and carbon (soot). These particles are most effective at absorbing light. These same particles are the most likely to enter the human lung and cause health effects in sensitive human populations. For this reason, the EPA recently set a new NAAQS for PM-2.5 (U.S. EPA 1998).

Since visibility and scenic vistas are important air quality-related values, the FLMs, in concert with the EPA, states and industries, created the Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring network. As part of the newly promulgated regional haze regulations (April 22, 1999), the total number of monitors in parks and wilderness areas will increase to 110, to be installed by early 2000.

A fully complemented IMPROVE site employs three types of monitors: photographic, optical and aerosol. Photographic monitoring documents the condition of a scenic vista in a park several times a day using a 35-mm camera. Optical monitoring directly measures the light extinction coefficient with transmissometers or the light scattering coefficient with nephlometers. The light extinction coefficient is a measure of the attenuation of light per unit distance caused by the scattering and absorption of gases and particles in the atmosphere. The scattering coefficient has a similar definition, except absorption is not included. Aerosol monitoring includes the collection of fine (PM-2.5) and coarse (PM-10) particles on different types of filters, which are analyzed for mass, chemical constituents, organics, elemental carbon and optical absorption. The concentrations of aerosol constituents are used to estimate their contributions to the light extinction coefficient, and allow for the plotting of "reconstructed extinction." For more information on the network and results of the analyses, see Eldred and Cahill (1994), Malm (1992) and Sisler and others (1996).

A sample of data collected at class 1 parks from 1991-1997 is included in Figure 2. This bar graph depicts the reconstructed extinction at 11 parks included in the park index site network, Park Research and Intensive Monitoring of Ecosystems Network (PRIMENet). The data are expressed as inverse megameters (Mm^{-1}), with Denali National Park having the lowest concentration of fine particles and extinction values that correspond to a 186-km standard visual range. At this "clean site," most of the light extinction is explained by atmospheric light scattering by gas molecules, know as Raleigh scattering. In contrast, park sites in the eastern U.S., especially Great Smoky Mountains and Shenandoah National Parks, show large extinctions associated with sulfate aerosol. The next largest contributors to visibility degradation at all the sites are organic carbon and soot, attributed to biomass burning and urban emissions.

The Clean Air Act Amendments (CAAA) of 1977 provide special protection for visibility in class 1 areas. There are two emission control programs specifically concerned with visibility in national parks and wilderness areas: the Prevention of Significant Deterioration (PSD) program (directed mainly at new sources) and the visibility protection program, which allows for control of existing sources of pollution (National Research Council 1993). The first major action under the CAAA provisions was the certification of visibility impairment in all NPS class 1 areas, including the Grand Canyon, by the Department of the Interior, assistant secretary for Fish, Wildlife and Parks in 1985 (Shaver and Malm 1996). After a series of intensive studies to determine the contribution of the Navaho Generating Station (NGS) to winter haze in Grand Canyon National Park, Canyonlands National Park, and Glen Canyon National Recreation Area, the EPA issued a proposed regulation to require a 70% reduction in NGS SO_2 emissions, to be achieved through the

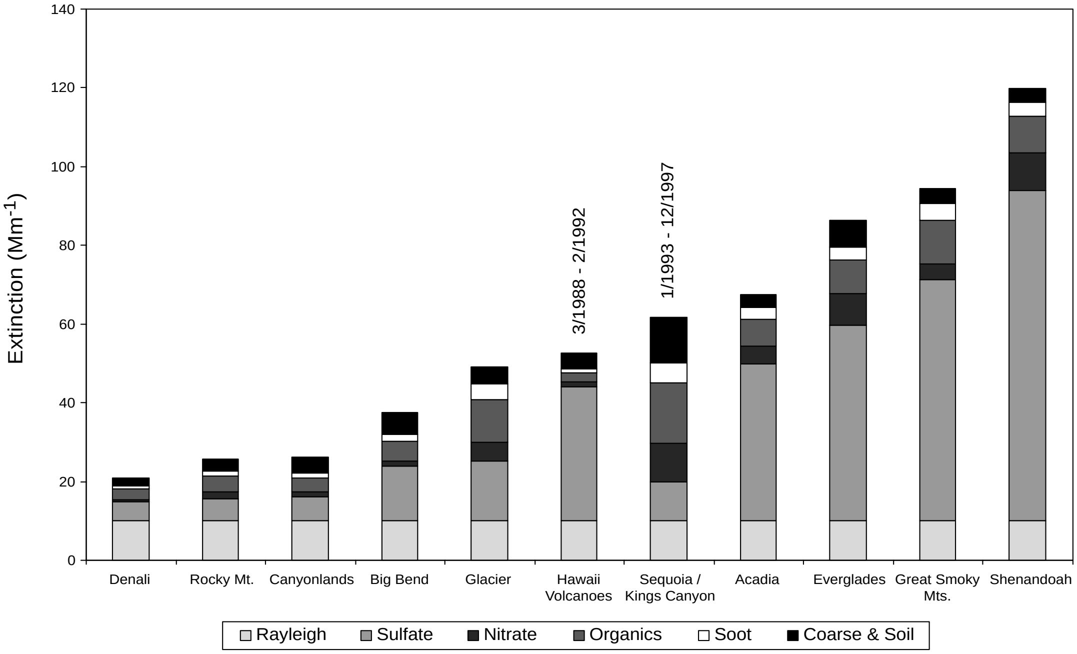


Figure 2—Average reconstructed extinction at PRIMENet sites, 1991-1997.

installation of scrubbers. Negotiations among industry, environmental groups and the EPA resulted in the recommendation of a 90% SO_2 reduction, with an initial delay in installation of the control equipment. This recommendation was adopted in the final regulation, announced by President Bush at the Grand Canyon in September 1991.

Federal land managers have tried this strategy to control large coal-fired power plants located upwind of class 1 areas. The USFS certified visibility impairment to the Mount Zirkel Wilderness Area in Colorado, due to SO_2 emissions from the Craig and Hayden power plants. A lawsuit by the Sierra Club, prompted by numerous violations of the opacity standard at Hayden, resulted in an agreement by the utility to install SO_2 and NO_x control equipment. SO_2 emissions from the Centralia power plant in Washington State were linked to visibility degradation at Mount Rainier National Park and several USFS wilderness areas in the Cascades. Through a "collaborative decisionmaking" process among all affected parties, there was an agreement to install scrubbers on this, the largest source of SO_2 in the West after NGS. In each case, special studies of visibility and other AQRVs were organized to allow for "attribution" to specific sources. This costly and time-consuming process led to the requirement in the CAAA of 1990 for the creation of a Grand Canyon Visibility Transport Commission (GCVTC 1996), which came up with recommendations to EPA on how to protect visibility in class 1 areas of the Colorado Plateau.

Many of these recommendations were included in the regional haze regulations announced by Al Gore on Earth Day 1999. This comprehensive approach to reductions in regional haze acknowledges the impairment of visibility at class 1 areas in all 50 states; its long-term goal is to return visibility conditions in the parks and wildernesses to "natural background." These regulations call for states to form regional groups to come up with pollution reduction strategies, which are likely to include the use of Best Available Retrofit Technology (BART) for existing point sources of pollution. One such regional group, the successor to GCVTC, is an association of Western states, now known as Western Regional Air Partnership (WRAP). For information on the new regional haze rules, see the EPA website: http:/www.epa.gov/ttn/oarpg.

2. Tropospheric or ground-level ozone: This is also a criteria pollutant, formed by the reaction of NO_x and volatile organic compounds (VOCs) in the presence of sunlight. Ozone is a strong oxidizing agent that affects human lung function and damages vegetation by entering through the stomates and causing cell death. This pollutant is transported to class 1 areas in proximity to urban areas, especially on the East and West Coasts. Ozone injury to native vegetation has been documented in parks and wilderness areas in California (Miller and others 1996) and in the Southeast (Chappelka and Samuelson 1998). The sensitive indicator plants include Ponderosa and Jeffrey pine in the West and hardwoods, such as black cherry and white ash, in the East. A number of understory plants, such as milkweed, asters and blackberry have shown visual injury symptoms due to ozone during controlled-fumigation experiments and in the field (Neufeld and others 1995). The response of vegetation to ozone exposure varies with other environmental conditions. For instance, during drought periods, plant stomates remain closed, cutting down on the uptake of ozone.

Ozone levels are typically reported in terms of the primary NAAQS set by EPA. The standard to protect human health was set at a one-hour average of 120 parts per billion (ppb); the new standard promulgated in 1997 is an eight-hour average of 80 ppb, considerably more restrictive. The setting of this new standard means that a number of class 1 areas may exceed the health standard for ozone. Note: the

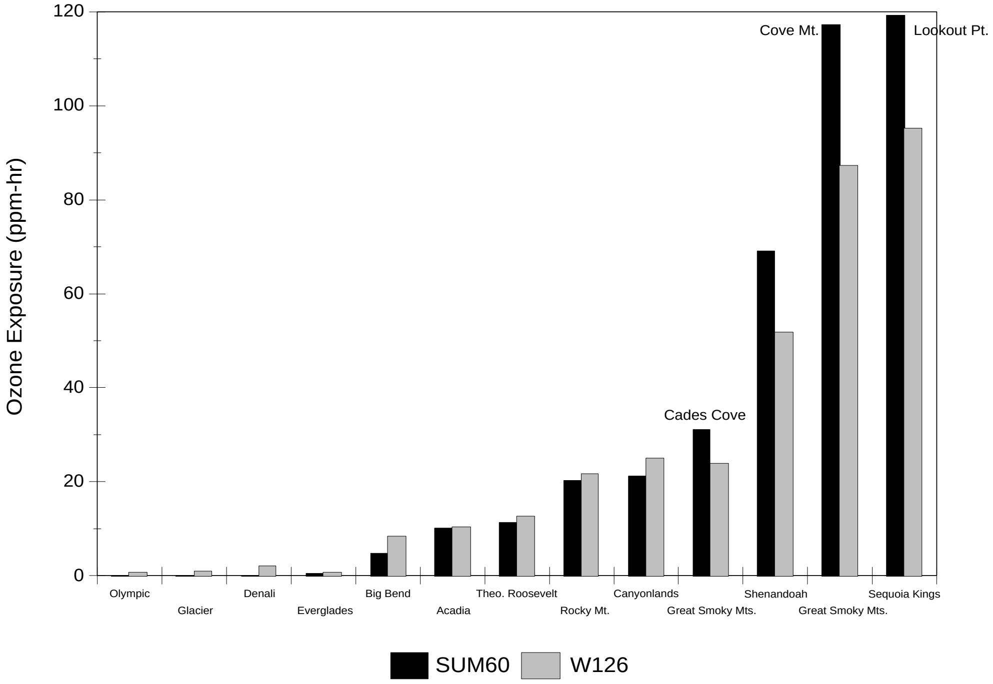


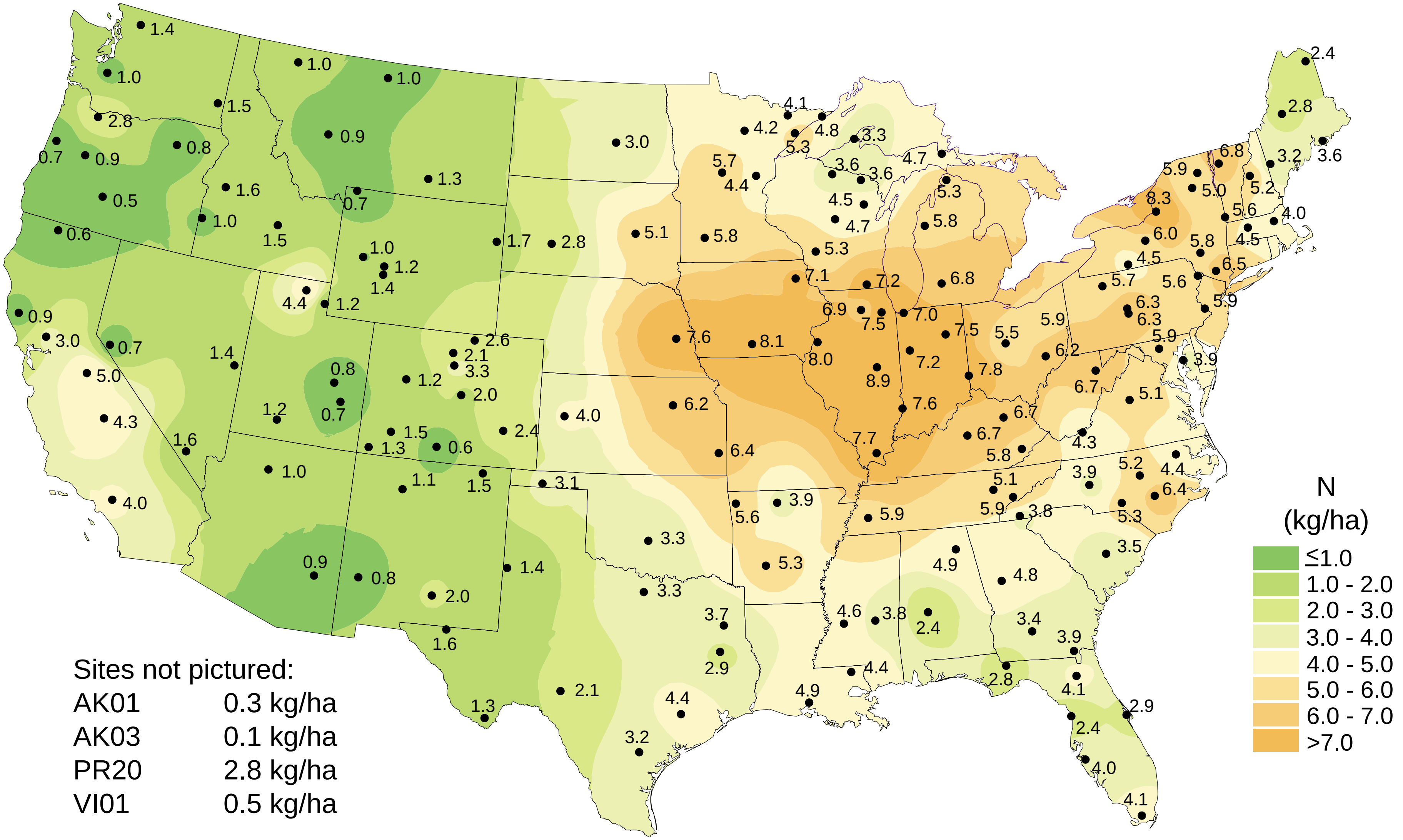
Figure 3—Ozone exposures at PRIMENet sites for the 1997 growing season.

standard has been challenged in court. Vegetation responds differently to ozone exposure, so scientists have come up with two integrating statistics to describe ozone levels during the growing season (U.S. EPA 1996a, 1996b). Figure 3 shows the calculated SUM60 and W126 indices for 12 PRIMENet parks for the 1997 growing season (May-September). The SUM60 is a sum of all hourly ozone concentrations equal to or exceeding 60 ppb; the W126 is the sum of all hourly ozone concentrations, weighted by a function that gives greater emphasis to concentrations above 60 ppb (Lefohn and others 1992). Lookout Point, in Sequoia National Park (CA) and Cove Mountain, in Great Smoky Mountains National Park (TN/NC), recorded the highest ozone exposures in 1997. These parks typically have sensitive vegetation that show ozone injury by the end of the growing season. The contrast between Cove Mountain and Cades Cove in Great Smoky Mountains National Park points out the influence of elevation on total ozone exposure. At most, if not all, sites monitored for ozone in mountain parks, the highest levels of ozone are measured at the higher elevations.

3. Deposition of sulfur and nitrogen compounds: Deposition includes chemical constituents that accumulate on surfaces, delivered via rain, snow, mist, fog, clouds and dry-deposited gases and particles. The most commonly measured form of deposition is wetfall, usually rain and snow, measured by the National Trends Network/National Atmospheric Deposition Program (NTN/NADP). NTN/NADP is a national network of monitors where wetfall is measured weekly, with samples sent to a Central Analytical Lab, in Champaign, IL, for analysis of chemical constituents, including pH (H ion), major anions (including sulfate and nitrate) and major cations (including calcium, magnesium, sodium and ammonium) (Lynch and others 1995). NTN/NADP includes more than 220 sites, primarily in rural areas, with many sites located in or adjacent to class 1 areas. The list of class 1 monitoring sites is included in the FLAG (1999) report.

Analytical products from the network include isopleths maps of chemical concentrations and wet deposition collected during each calendar year (NADP 1999). These maps, such as the one shown in Figure 4, allow for regional assessment of pollutant loading. The map shows 1997 deposition of nitrogen in rain and snow.

Another way of presenting the data is to compare volume-weighted, average concentrations of selected constituents across sites (Figure 5). This plot of nitrate and sulfate in precipitation averaged over the period of 1984-1997 shows the relative loading of these two pollutant species across a number of NPS class 1 areas. The lowest mean concentrations of nitrate in rain were recorded at Olympic National Park (WA) and Denali National Park (AK). Many of the parks throughout the country show similar nitrate concentrations (10-15 ueq/l), with Sequoia-Kings Canyon National Parks (CA) and Rocky Mountain National Park (CO) (Beaver Meadow site) having more nitrate than sulfate in rain. The spatial patterns in rainfall sulfate concentrations at these parks reflect the influence of sulfur emissions in the eastern U.S. and the U.S./Mexico border region. Two of the national parks with the highest sulfate concentrations, Great Smoky Mountains and Shenandoah National Parks, are also the parks that have adverse impacts to their natural resources as a result of acidic deposition. In Shenandoah National Park streams are experiencing both chronic and episodic acidification (Bulger and others 1998), and there are documented effects on fisheries in the park. In Great Smoky Mountains National Park nitrate is leaking out of watershed soils into streamwater, causing episodic acidification. There is also evidence that soil water is acidified by



Sites not pictured:

AK01	0.3 kg/ha
AK03	0.1 kg/ha
PR20	2.8 kg/ha
VI01	0.5 kg/ha

National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Figure 4—Estimated inorganic nitrogen deposition, NTN/NADP, 1997.

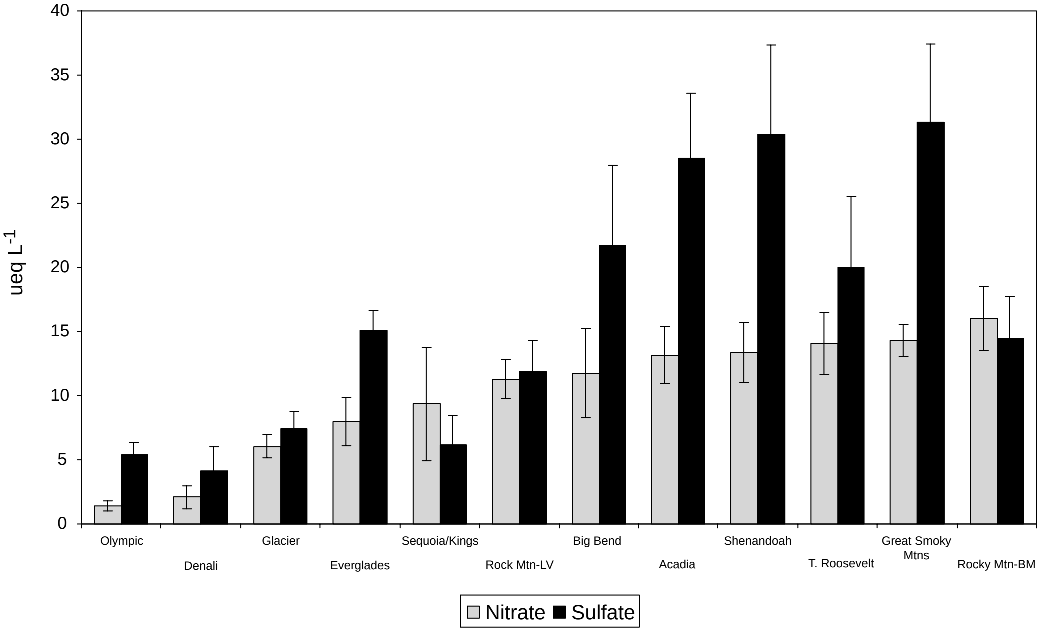


Figure 5—Average annual concentrations of nitrate and sulfate in precipitation, 1984-1997.

deposition, as evidenced by the indicator of terrestrial health, the calcium to aluminum ratio (Johnson and others 1991; van Miegroet and others 1992).

The data summarized in Figure 5 focus on nitrate and sulfate because these are the two chemical constituents that contribute to acid loading and are "acid anions," which can leach nutrients such as calcium and magnesium from the soils (Lawrence and Huntington 1999), and contribute to acidification of freshwaters characterized by low buffering capacity or acid-neutralizing capacity (ANC). Nitrate can also act as a fertilizer, especially in waters where phosphorus is abundant, as in the case of many estuaries along the Atlantic and Gulf Coasts (U.S. EPA 1994, 1997).

From an ecosystem perspective, it is important to determine the total amount (or loading) of these chemicals to sensitive ecosystems in protected areas. The NTN/NADP data summaries include estimates of deposition of nitrogen and sulfur in wet deposition, based on the amount or rain or snow that fell at that point. For many class 1 areas, especially in mountainous terrain, the greatest loading comes in the form of seasonal snow (Elder and others 1991). There are sampling problems in snow collection using NTN/NADP buckets at high-elevation sites (Williams and others 1998). In some Western mountain ranges, chemical loading in seasonal snowpacks in estimated at maximum accumulation, which allows for measurement of both wet and dry deposition during the snow-covered period (Heuer and others 2000; McGurk and others 1989).

There are protected areas where rain and snow are small contributors to total chemical deposition from the atmosphere. Many of these sites are now included as part of a national dry deposition network, known as the Clean Air Status and Trends Network (CASTNet), with a number of partner agencies, including EPA-Office of Air and the National Park Service (Lear and Frank 1998). National Parks class 1 and 2 areas that have a dry deposition filter pack in or adjacent to them include: Big Bend National Park (TX); Canyonlands National Park (UT); Chiracahua National Monument (AZ); Death Valley National Park (CA); Everglades National Park (FL); Glacier National Park (MT); Grand Canyon National Park (AZ); Great Smoky Mountains National Park (TN/NC); Hawaii Volcanoes National Park; Joshua Tree National Park (CA); Mesa Verde National Park (CO); Mount Rainier National Park (WA); North Cascades National Park (WA); Olympic National Park (WA); Pinnacles National Monument (CA); Rocky Mountain National Park (CO); Sequoia-Kings Canyon National Parks (CA); Shenandoah National Park (VA); Voyageurs National Park (MN); Yellowstone National Park (WY); Yosemite National Park (CA); Acadia National Park (ME); Denali National Park (AK); Virgin Islands National Park; Chiracahua Wilderness Area (AZ); and Lye Brook Wilderness Area (NH).

CASTNet sites include a three-stage filter pack that collects particles and gases, including nitric acid, particulate nitrate, sulfur dioxide and particulate sulfate. These sites typically include a continuous ozone monitor and meteorological instruments that collect data needed to run the models used to estimate deposition from the ambient measurements. Both an Eastern park (Shenandoah National Park (VA)) and a Western park (Sequoia-Kings Canyon National Parks (CA)) have the highest concentrations of nitrogen species in ambient air. By summer 1999, the CASTNet website will include dry deposition estimates derived for network sites using the NOAA "big leaf" model.

4. Toxic air contaminants are defined in the CAAA of 1990, which identifies 188 substances that need to be controlled to protect human health. However, the regulatory approach used to control emissions of these substances (also called persistent toxic substances) is based on technology controls of emissions from the major sources of these pollutants, such as power plants, industrial facilities, incinerators, and smelters. The toxic air contaminants that have

the most relevance to class 1 area resources are mercury, dioxin, chlordane and PCBs (polychlorinated biphenyls). These are substances that travel long distances from sources and bioaccumulate in fish and other wildlife. Thirty states have consumption advisories for specific waterbodies to warn consumers about Hg-contaminated fish and shellfish (U.S. EPA 1994, 1997).

The toxic air contaminant that has received the most attention from FLMs and state managers of fish and game is mercury (Hg). This toxic metal accumulates in fish and wildlife tissue and is a potent neurotoxin. Hg has many natural and man-made sources and has a complicated geochemical cycle. It is emitted from large point sources such as electrical-generating plants, chlor-alkai plants and waste incinerators. But is also emitted during forest fires, and from degassing of soils. High concentrations of Hg have been measured in sediments and fish tissue in certain remote parts of the high Arctic (Landers and others 1998). In recognition of its importance, federal and state agencies, Canadian agencies, universities and industry partners set up the Mercury Deposition Network (MDN) in 1996, as a sub-network of the National Atmospheric Deposition Program, to measure the annual concentration and deposition of Hg in wetfall (Sweet and others 1998). It is important to note that due to its high volatility, the predominant form in the atmosphere is gaseous Hg. This form of Hg can be transported long distances, and has a low solubility in water, and is therefore not efficiently scavenged by rainfall (Brosset and Lord 1991).

Figure 6 shows the distribution of Hg deposition among the 30 MDN sites. A number of FLM areas are included in the network: Everglades National Park (FL), Acadia National Park (ME), Congaree Swamp NM (SC), Okefenokee National Wildlife Refuge (GA), Chassahowitzka National Wildlife Refuge (FL) and Mount Zirkel Wilderness Area (CO). Data for annual deposition (ug/m2) in 1997 show the highest loading for Everglades National Park.

One class of toxics that is of current concern to natural resource managers is endocrine-disrupting compounds (EDCs). These are complex, organic compounds that “mimic” estrogens and can affect reproductive systems in wildlife and humans (Colborn and Clement 1992). These compounds include dioxin, DDT, DDE and other pesticides. Recent studies indicate that these compounds have wide distribution in the environment and are scavenged by snow in high-elevation regions in the mid-latitudes (Blais and others 1998).

Routine monitoring for toxic substances is limited. The EPA is setting up a national dioxin monitoring network, called National Dioxin Air Monitoring Network (NDAMN). Some class 1 areas, such as Big Bend National Park (TX), Everglades National Park (FL); Craters of the Moon National Monument (ID); and Grand Canyon National Park (AZ), have been proposed as network sites because they meet the siting criteria outlined in the EPA’s Dioxin Exposure

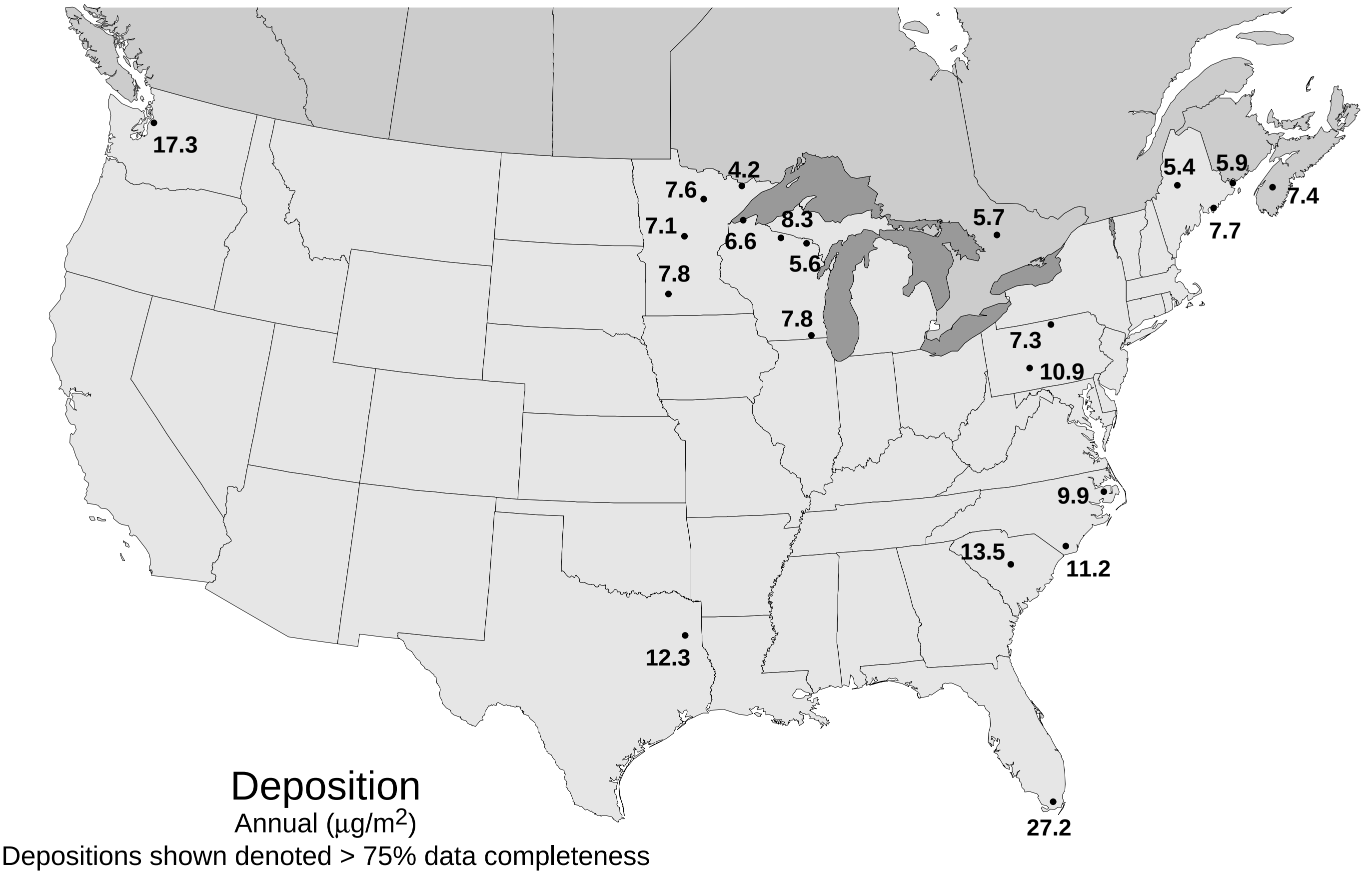


Figure 6—Annual deposition of mercury, 1997.

Initiative. The NDAMN sampler is the PUF (poly-urethane foam), which collects particle and vapor-phase pesticides.

The only long-term toxics monitoring network is sponsored by the EPA in the Great Lakes region. The Integrated Atmospheric Deposition Network (IADN) includes one site on each of the Great Lakes on both sides on the border. Sleeping Bear Dunes National Lakeshore (MI) is the IADN site on Lake Michigan. This network tracks both inorganic and organic pollutant trends and is associated with the Great Lakes Water Quality Agreement signed by the U.S. and Canada. The Commission on Environmental Cooperation (CEC), created by the NAFTA "side agreement" on environment, is planning a trilateral air monitoring network to measure toxic air contaminants in Canada, the U.S. and Mexico (CEC 1998).

In summer 1998, the NPS and the EPA collaborated in a contaminant screening study to collect and analyze organic and inorganic pollutants in various media, including water, sediment, fish and vegetation in 12 class 1 areas. The project is part of the index site network, Park Research and Intensive Monitoring of Ecosystems. Data from this "screening" study are expected in summer 2000.

Global Air Pollutants—These air pollutants fall into two classes: ozone-depleting compounds (ODCs) and greenhouse gases, including carbon dioxide, methane and nitrous oxides. These air pollutants tend to be long-lived in the atmosphere and have the ability to travel globally in both the troposphere and the stratosphere (upper layer of the atmosphere).

Ozone-depleting compounds include chlorofluorocarbons (CFCs) and freons. They are used in refrigeration and as solvents. These substances are transported to the stratosphere, where they chemically destroy the protective ozone that filters out UV light (WMO 1994). In 1985, the scientific community discovered the stratospheric ozone "hole" over the Antarctic, which resulted in more damaging UV-B reaching the surface of the earth. Ozone thinning has been detected throughout the globe, with seasonal depressions in this protective shield being most severe at the poles (Madronich 1993). In 1987, the major industrial nations signed the Montreal Protocol on Substances that Deplete the Ozone Layer, which calls for a phase-out of CFCs. Because of the long lifetimes of CFCs in the upper atmosphere, it is not known when the ozone thinning will be reversed. In the mid-latitudes of the U.S., UV-B levels have increased 4-5% over the past 10 years (U.S. EPA 1998).

Effects of UV-B on biological systems include: increases in human skin cancers and cataracts, damage to phytoplankton and reduction in growth of fish, molluscs and crustacea, damage to DNA and photosynthesis in plants and possible effects on animals, including benthic invertebrates and amphibians (Tevani 1992; Williamson and Zagarese 1994).

Because they are located relatively distant from local pollution sources, 14 class 1 parks were selected by the EPA as UV monitoring sites. These parks are part of a larger index site network known as Park Research and Intensive Monitoring of Ecosystems Network (PRIMENet) (see map of sites in figure 7). Each site is equipped with a Brewer

Figure 7—Map of NPS/EPA PRIMENet sites.

spectrophotometer, an instrument designed to measure different wavelengths of light, with a focus on the ultraviolet spectra (UV-B radiation is in the 300-320 nm range of light). These instruments track the sun as they monitor the variation in solar irradiance throughout the day; they also record other data, such as total column ozone and ambient concentration of gases. These data are then used to calculate the "dose" of UV at the surface of the earth. Because of the influence of sun angle, clouds and other forms of air pollution, the seasonal variation in UV-B detected at the surface is large, as shown in the annual data. Therefore, it will take many years of monitoring to detect trends in the incidence of UV-B.

The PRIMENet sites complement a larger Brewer network in the U.S. that includes seven monitors located in cities. These monitoring devices have also been deployed in Canada and on other continents, to allow for a global assessment of the status of the stratospheric ozone layer (Wilson and others 1992).

The major pollutant gas contributing to global warming (85 % of total) is carbon dioxide (CO_2), produced during the combustion of fossil fuels. Methane (CH_4) is the second largest contributor to greenhouse gas emissions. This compound is emitted from agricultural lands, landfills and natural wetlands. There is scientific consensus among the scientists who drafted the report of the Intergovernmental Panel on Climate Change (IPCC) in 1995 that "climate change is likely to have wide-ranging and mostly adverse impacts on human health, with a significant loss of life." Satellite observations indicate that growing seasons in the high latitudes may have increased by 12 days from 1981-1991 (Myneni and others 1997). Snowcover in the northern hemisphere appears to have retreated by 10% between 1972-1992, likely affecting boreal and arctic ecosystems (Groisman and others 1994).

The U.S. is being called on under the Kyoto Protocol (1997) to reduce greenhouse gas emissions to 7% below the base year of 1990. The U.S. "Climate Change Action Program," devised in 1993, resulted in a 15-million ton reduction in greenhouse gases during 1997 (U.S. EPA 1998).

Emission Sources—Power plants: Nationally, power plants account for the majority of SO_x and CO_2 emissions and significant amounts of NO_x and Hg (U.S. EPA 1998). Power plants burning fossil fuels contribute an estimated 67% of SO_x, 28% of NO_x, 35% of CO_2 and 33% of mercury (although there is considerably uncertainty in the emission inventories, especially for Hg). Most of the point source SO_x and NO_x is emitted from coal-burning power plants built before 1980. Other major point sources of these criteria pollutants include smelters, refineries and industrial facilities. Under the Clean Air Act and its amendments, new facilities are required to install clean technology; under the CAAA of 1990, identified sources are scheduled to install retrofit technology or use cleaner fuels to achieve targeted reductions. However, there is a class of power plants that was "grandfathered" under the CAAA, those in operation before the mid-1980s. Many of these plants, especially in the eastern U.S., are operating past their 30-year projected life span and, therefore, are the major sources of acid deposition precursor emissions.

Mobile sources: Fuel combustion in the transportation sector is the largest contributor to NO_x emissions; stationary combustion sources account for most of the remaining emissions. In the period of 1988-1997, there was a 1% decrease in NO_x emissions in the U.S. (U.S. EPA 1998). Two recent developments in the regulatory arena are likely to control growth or reduce NO_x emissions. In 1998, the EPA called on the 22 Eastern states to revise their State Implementation Plans (SIPs) to reduce NO_x emissions in the summer to achieve reductions in ozone. This control strategy resulted from modeling analyses performed by the Ozone Transport Assessment Group (OTAG). In May 1999, President Clinton announced new auto emission rules that will require cuts in NO_x emissions from light-duty trucks and more stringent levels of these emissions overall from the fleet, beginning in 2004. SO_x emissions from vehicles will be reduced under the proposed rule to cut the sulfur in gasoline from an average of 300 ppm (parts per million) to 30 ppm by 2004. This measure is recommended primarily to prevent "poisoning" of the catalytic converters in vehicles.

Air Quality-Related Values (AQRVs)—These are the wildland resources that federal land managers are required to protect from air pollution injury. These are generally defined in the CAAA as visibility, flora, fauna, water quality, soils, wildlife, odor and ecosystem integrity. These are being further defined by the FLMs to include lists of sensitive indicators and the levels of pollution that will affect these indicators. The FLAG effort is designed to coordinate the development of lists of sensitive indicators and pollution levels of concern, known as "critical loads," "critical levels," "screening level values" or "thresholds." The most current information is summarized in the FLAG, Phase 1 report (FLAG 1999), with more detailed information included in an array of synthesis documents prepared in the last decade by the USFS (Adams and others 1991; Fox and others 1989; Haddow and others 1998; Peterson and others 1993; Peterson and others 1992; Stanford and others 1991; Turner and others, in preparation), the NPS (Binkley and others 1997; Eilers and others 1994; Peterson and others 1998) and the FWS (Porter 1996).

Natural resources and scenic values most at risk from regional air pollution include: the effects of fine particles on visibility, the effects of ozone on native vegetation, the effects of deposition on surface waters, estuaries and terrestrial systems and the bioaccumulative effects of toxics, such as mercury and chlorinated organics, on aquatic organisms.

Deposition of Sulfur and Nitrogen as a Case Study

History of Deposition Research

"Acid rain," the deposition of acidic compounds of nitrogen (N) and sulfur (S), was first recognized to have ecological consequences as a result of early studies in Europe. In the U.S., monitoring of precipitation chemistry began in 1978, in response to scientific concern about this stressor. The wet deposition network, known as National Atmospheric Deposition Program (Lynch and others 1995), is the longest running environmental chemistry network in the U.S. The Canadians, concerned that U.S. air pollution was affecting their natural resources, also set up a deposition chemistry network and defined a "target load" of wet sulfate deposition of 20 kg/ha/year to control damage to lakes in the eastern provinces (Environment Canada 1998). The Canadians have since refined their assessment of the response of lakes to acidic deposition and have set a critical load of 8 kg/ha/year to protect the most sensitive systems.

The measurement and monitoring of deposition inputs in North America has progressed beyond monitoring of wet deposition alone to include national networks to measure dry deposition (Clean Air Status and Trends Network, CASTNet), daily wet deposition inputs (Atmospheric Integrated Research Monitoring Network, AIRMon) and mercury (Mercury Deposition Network, MDN) (Sweet and others 1998). Additional deposition data are available from short-term and regional networks to measure cloudwater (Mountain Cloud Chemistry Network and CASTNet), snowpack chemistry in the Rockies (Rocky Mountain Synoptic Snow Network) (Ingersoll 1995) and various forms of deposition in California (Blanchard and others 1996; Blanchard and Tonnessen 1993; California Air Resources Board 1993). Class 1 areas in the U.S. are relatively well-characterized with respect to rain, but few parks and wilderness areas monitor clouds, fog, dry deposition or toxic air contaminants on a routine basis as part of a national, quality-assured networks (Federal Land Managers AQRV Working Group 1999).

Research on the effects of acid deposition began in earnest in the U.S. with the passage by Congress of the Acid Precipitation Act of 1980. This legislation authorized a $500 million research program over a 10-year period. During that time, the National Acid Precipitation Assessment Program (NAPAP) provided funding and direction for 12 federal agencies and hundreds of scientists, both within agencies and outside. This was one of the first experiments with "policy-relevant" research and assessment (Winstanley and others 1998). The final assessment (National Acid Precipitation Assessment Program 1991) and 13 State-of-Science and Technology documents were the products of this scientific effort, which was not without its critics. The results of this research, monitoring and modeling exercise was the Clean Air Act Amendments of 1990, which called for a 10-million ton reduction in SO_x emissions and a two million ton reduction in NO_x emissions in order the reverse the effects on lakes, streams, fish and watersheds soils that were documented in the eastern U.S. and Canada. One provision in the CAAA reauthorized NAPAP to perform periodic assessments of the effectiveness of these emission reductions. The first of these "follow-up" assessments was completed in 1998 (National Acid Precipitation Assessment Program 1998); the next is scheduled for 2000.

At the end of the first 10 years of NAPAP, the scientific community realized that they had not paid sufficient attention to the impacts of nitrogen deposition on freshwaters, terrestrial systems and estuaries (Fenn and others 1998; Vitousek and others 1997). The Forest Response Program (Bernard and Lucifer 1990) and the Episodic Response Program (Wigington and others 1990) were just starting to publish results when NAPAP came to the end of its 10-year funding. Since 1990, there have been additional studies to investigate streamwater episodic acidification and the further development of models to improve prediction of surface water acidification (i.e., MAGIC model: Model of the Acidification of Groundwater in Catchments) (Cosby and others 1995; Sullivan and Cosby 1995).

Since much of the deposition monitoring and effects research under NAPAP focused on the eastern U.S., there was little information generated about how deposition affects the western U.S., the location of the largest number of class 1 parks and wilderness areas. With the exception of the Western Lake Survey (Eilers and others 1988; Landers and others 1987), little attention was paid to low-acid neutralizing waters in the Sierra Nevada, Cascades, and Rocky Mountains. Even less is known about forest and grassland status relative to deposition in the Southwest and the Colorado Plateau, home to a large number of class 1 parks and wilderness areas. Coastal wilderness areas managed by the FWS were not included in research programs funded under NAPAP. In subsequent assessments and programs, these data gaps are being filled. The EPA's report on deposition standards (U.S. EPA 1995) began to recognize the role of nitrogen in altering ecosystem processes in Western mountains. There was also a realization that wet deposition inputs in the sensitive, high-elevation areas of the West were dominated by snow and required a different type of deposition monitoring and a different approach to effects research (McGurk and others 1989; Sickman and Melack, 1998; Williams and others 1996b).

Without a national research program dedicated to investigating deposition effects on natural resources, we are left with a patchwork of research and monitoring programs, with NAPAP existing on paper as the "clearinghouse" for research results. Under the CAAA of 1990, NAPAP is still required to carry out periodic assessments of the effects of deposition, with funding and personnel to write the assessments provided by federal agencies. The next assessment, scheduled for the year 2000, will further investigate the progress of ecosystem recovery with reductions in SO_x emissions.

The focus of deposition research and data analysis has shifted to regional assessments, such as the Southern Appalachian Assessment (Southern Appalachian Mountains Initiative 1999). These regional assessments make use of existing models and field data on ecosystem response to deposition. No new data are generated during these exercises. To advance the science of deposition effects on resources, the FLMs rely on the "science" and research arms of their respective agencies; U.S. Geological Survey for the Department of the Interior, and USFS research stations for the USFS. The FLMs have also been able to attract research and monitoring programs funded by other federal agencies, such as Environmental Monitoring and Assessment Program (EMAP), PRIMENet and Global Change programs under the EPA-Office of Research and Development and the Long Term Ecological Research program, funded by the National Science Foundation. Parks and wilderness areas have also served as "ground truth" sites for NASA satellites and remote sensing instruments, such as LANDSAT, SAR (Synthetic Aperture Radar) and AVHRR (Advanced Very High Resolution Radiometer). Some of the NASA-Earth Observing System investigations have focused on class 1 areas, such as Sequoia-Kings Canyon National Parks (CA), Glacier National Park (MT) and Rocky Mountain National Park (CO). With the launch of the TERRA earth-observing platform in 1999, there are more opportunities for collection

Table 1—Milestones in science and policy related to nitrogen and sulfur deposition.

1970	Clean Air Act (CAA)
1977	CAA Amendments (CAAA); Class 1 areas designated
1978	National Atmospheric Deposition Program (NADP) initiated
1980	National Acid Precipitation Assessment Program (NAPAP) starts
1990	CAAA passed; acid rain control program
1991	NAPAP Integrated Assessment published
1991	US/Canada Air Quality Accord signed
1992	Southern Appalachian Mountains Initiative (SAMI) begun
1995	EPA's Deposition Standards Report published
1997	New NAAQS for Ozone and PM-2.5 announced
1997	Class 1 Area managers form Federal Land Managers' Air Quality Related Values Work Group (FLAG) to address consistency in approach to AQRV protection
1998	NAPAP Assessment Report published
1998	NO_x SIP Call announced by EPA
1999	Final Regional Haze Regulations for Protection of Visibility in National Parks and Wilderness Areas.
1999	New vehicle emission rules; fuel standards
1999	Court decision questions basis for new NAAQS

of remote-sensing data on sensitive mountain ecosystems in the West.

For a tabular history of both research and regulatory developments in the area of deposition effects on resources, see Table 1.

Deposition Monitoring and Research Results

What We Know About Deposition

Deposition of N and S and Its Effects—A thorough discussion of regional wet and dry deposition and its effects on watersheds and surface waters is found in Charles (1991), with information on class 1 areas containing sensitive lakes and streams in the eastern U.S. (Mid-Atlantic Highlands) and in the western U.S. (Rockies, Cascades and Sierra Nevada). An update of "what we know" is included in the recent NAPAP assessment (1998). Chemical species in deposition that determine the "dose" to the ecosystem are: hydrogen ion (pH), sulfate, nitrate and ammonium.

In general, acidity in rain and snow can affect soil fertility and nutrient cycling processes in watersheds. Acidity in rain and snow can result in acidification of low-acid neutralizing capacity (ANC) lakes and streams, either of a chronic nature or episodically. In the mountainous areas in the western U.S., the total loading of wet deposition is high, but the concentrations of hydrogen ion at present are low, resulting is a relatively small total load of solutes to these systems. However, in the eastern U.S. at "high" elevations in parks and wilderness areas of the Southern Appalachians, total deposition of acidity and solutes is high due to a combination of inputs from dry, wet and cloudwater deposition (Johnson and Lindberg 1992). The other factor that must be considered in estimating the "load" of hydrogen ion to the ecosystem is the timing of the precipitation. In high-elevation regions, especially in the West, much of the annual precipitation is snow, which accumulates in a seasonal snowpack and then melts during a relatively short period in the spring. Any acidity in the snowpack that is not buffered in-situ is likely to come out as a concentrated "pulse" of acidic meltwater. This snowpack melting phenomena tends to exacerbate the effect of chemical loading to the pack (Bales and others 1993; Wigington and others 1996).

Another important chemical species in deposition is nitrogen. Deposition of excess nitrogen (nitrate and ammonium) to both terrestrial and aquatic systems can result in: (1) fertilization or eutrophication, and (2) episodic acidification of streams and lakes (Stoddard 1994). The role of ammonium in acidification and nitrogen leakage from ecosystems had been largely ignored in discussions of pollutant impacts in the eastern U.S. (NAPAP 1991). However, in Western locations, such as the Sierra Nevada and the Colorado Rockies, the ratio of nitrate to ammonium in wet deposition is frequently 1. The reaction of nitric acid with ammonia gas emitted from feedlots and fertilized fields results in formation of ammonium nitrate particles, which can be carried long distances before being deposited in remote watersheds. When this buffered compound reaches soils and surface waters, the ammonium is preferentially taken up by biota, thus generating acidity. It is possible for ammonium nitrate transformation and transport to deliver nitrogen species to parks and wilderness areas in some regions of the country, such as the Sierra Nevada and the Front Range of Colorado, depending on the pattern of local ammonia emissions relative to the supply of nitric acid vapor.

Changing Composition of Deposition—We now have sufficient years of data as part of NTN/NADP to plot trends in wet deposition. Lynch and others (1995; 1996) performed an analysis of the trends in wet deposition chemistry for the period 1983-94 and then continued to track wetfall trends for eastern U.S. sites to look for evidence of the 1995 SOx emission reductions required under the CAAA. The general pattern nationally was a trend toward decreases in sulfate in rain and snow, with little change in nitrate concentrations. Over large areas of the eastern U.S. there were 10-25% decreases in sulfate wet deposition, especially downwind of the Ohio River Valley. Some sites in the network showed increasing concentrations of ammonium. The surprise in the analysis was a general decrease in the concentrations of base cations (calcium, magnesium, sodium and potassium) in rainfall, especially in the Northeast. This general trend was also noted in Europe (Hedin and Likens 1996; Hedin and others 1994). Even wilderness sites in "background" areas, such as Denali National Park (AK) and the Pacific Northwest (Olympic, Mount Rainier and North Cascades National Parks) showed low concentrations of inorganic nitrogen, but with evidence of an increasing trend (Lynch and others 1995). It is not likely that the small emission reductions of NO_x required under the CAAA (a cut of 2 million tons) will result in reductions of N species in rain.

Differences in Types of Deposition—Most of the research and monitoring on deposition focused on regions where rain inputs are the major form of deposition, especially in the Northeast, where most of the acidified waters are found. As NAPAP progressed, there was more information available on major chemical loading coming into sensitive ecosystems in the form of dry deposition, snow loading and cloudwater. On ridges and mountain tops in the eastern

U.S., there can be considerable deposition of S and N from cloudwater (Johnson and Lindberg 1992; Lovett and others 1999; Vong and others 1991). However, these inputs are extremely variable in time and space, depending on the characteristics of the forest canopy. Because of the large heterogeneity and presence of "hotspots" in dry deposition and cloudwater deposition across landscapes, it is likely that models or statistical extrapolation may be preferable to direct monitoring of these inputs (Lovett and others 1999). The role that dry deposition plays in chemical loading to deserts and aridlands, such as the Colorado Plateau parks and wilderness areas, is now being investigated at sites throughout the Southwest, where both NTN/NADP and CASTNet sites have been installed.

The other major form of chemical loading to sensitive ecosystems is snow, which accumulates in seasonal snowpacks and then melts during a short period in the spring (Campbell and others 1995; Elder and others 1991). In extreme cases, such as in the alpine of the Sierra Nevada and the Cascades, as much as 90% of the total precipitation annually can be in the form of snow. However, there is interannual variability in these inputs, with the prospect that Western mountains will receive more rain and less snow because of increasing global temperatures. Large episodes of snowmelt runoff in the spring affects stream and lakewater hydrology and chemistry. In the Western mountains, researchers have observed loss of ANC and depression in pH in surface waters, caused by both elution of ions and dilution by snowmelt (Sickman and Melack 1998; Stoddard 1995; Turk and Campbell 1987).

Reducing Sulfur Emissions Affects Surface Waters—The recent NAPAP assessment (1998) points out that the reduction in sulfur emissions under the CAAA has been translated into a reduction in sulfate concentrations in deposition and in stream and lake waters in the northeastern U.S. and Canada (Stoddard and others 1998). What was unexpected was the general lack of recovery of pH and ANC in many of the affected water bodies in this region. There are a number of hypotheses to explain this phenomena, including the reduction in base cations in deposition (Hedin and others 1994) and the leaching loss of cations from the soil, resulting in less buffering of incoming acidity (Lawrence and Huntington 1999). The general conclusion is that the reductions in SOx emissions may be inadequate to improve the acid-base status of freshwaters in the eastern U.S. and Canada. The Canadians arrived at the same conclusion in their acid rain assessment (Environment Canada 1998), and are calling for another round of sulfur emission reductions in both countries, and a revision in the critical loads of S needed to protect the most sensitive lakes in the eastern provinces, in areas such as Kejimkujik National Park (Nova Scotia).

Identity of Sensitive AQRVs—The considerable research on natural ecosystems pursued under NAPAP, the Great Waters Program and state agency programs, such as the California Air Resources Board's, Acid Acidity Protection Program (CARB 1993), has given us a general list of ecosystem components that respond to deposition of sulfur and nitrogen.

1. Freshwater lakes and streams, having ANCs less than 50 ueq/l.

2. Aquatic biota, especially fish (Bulger and others 1998), zooplankton (Engle and Melack 1995) and aquatic invertebrates (Kratz and others 1994).

3. High-elevation watersheds soils, especially in alpine areas and in the spruce-fir zone in the eastern U.S. (Brooks and others 1996; Eager and Adams 1992).

4. Estuaries, which respond to nitrogen inputs by producing algal blooms, oxygen depletion of bottom waters and loss of fish and shellfish (U.S. EPA 1994; 1997).

Indicators of Surface Water Acidification—Lake and stream chemistry responds to increases in deposition of N and S. The chemical changes include loss of ANC, lowered pH, increases in sulfate concentrations and increases in aluminum. Both chronic and episodic changes in water chemistry can affect aquatic organisms, including fish, plankton and aquatic insects. But the response of aquatic biota is variable, depending on other environmental factors, such as drought, floods, organic content of the water and available refugia for fish. The most successful way to identify sensitive biota and to determine their response to acidification is to conduct controlled and replicated in-situ or laboratory experiments (Barmuta and others 1990; Kratz and others 1994). Controlled experiments indicated the lack of response of amphibian species in the Sierra Nevada to episodic acidification (Bradford and others 1994), even though this was a plausible hypothesis at the outset of the study.

Indicators of N Fertilization and N Saturation—The AQRVs that were not well-defined under the first NAPAP (1991) are indicators of estuary health, which respond to nitrogen inputs. Through a combination of monitoring, research and modeling as part of the Great Waters Program (U.S. EPA, 1994; 1997), there is an increased awareness of how deposition of nitrogen in the form of nitrate and ammonium to both water surfaces and watersheds is affecting the biological and chemical status of estuaries and near-coastal waters. A number of FWS wilderness areas along the Atlantic and Gulf Coasts include significant estuary resources that may be affected by deposition of nitrogen (Dixon and Esteves 1998).

Most of the research on estuary response to N inputs has been conducted in the Chesapeake Bay, the largest estuarine system in the contiguous U.S., with a watershed of almost 64,000 square miles, encompassing 1/6 of the Eastern seaboard. Recent results have been obtained from integrated modeling of deposition of nutrients to the bay surface and to the watershed using the Regional Acid Deposition Model, along with water quality and sediment exchange modeling. The models show that a reduction of 20-30% in N and P loadings would result in improvement in dissolved oxygen status. Other models indicate that 30-40% of the N that reaches the bay was deposited from the atmosphere either directly on the water or to the extensive watershed (National Acid Precipitation Assessment Program 1998).

Grassland species diversity and ecosystem function were investigated in a series of N addition experiments in the upper Midwest (Tilman and others 1997; Wedin and Tilman 1996). Simulated N deposition resulted in a change in species diversity, favoring the more opportunistic and "weedy" species, although overall biomass was not significantly affected. These kinds of ecosystem process experiments are valuable, but it is difficult to devise an easily monitored indicator based on these findings.

Watershed Processes Control Chronic and Episodic Acidification—Most deposition comes in contact with soils before entering surface waters. The severity and type of acidification are determined by hydrologic flow paths through watershed soils. These flowpaths are influenced by climate, precipitation and soil strata. To understand acidification dynamics, researchers have used both naturally occurring isotopes of hydrogen, oxygen, nitrogen, and sulfur and labelled compounds (Kendall and others 1995; Williams and others 1996a).

Depending on the regional hydrology and deposition regimes, sensitive systems may be subject to either chronic and episodic acidification. We find chronically acidic lakes and streams in the eastern U.S., with some streams in Shenandoah National Park having ANC of 0 or less year round, the major acid anion being sulfate. Low-ANC systems found at high elevations in both Eastern and Western wilderness areas and parks are susceptible to episodic acidification associated with intense rains or spring snowmelt. Under this scenario, acidic rain events or the first "pulse" of acidic water from snowpack melting enter low-ANC waters and depress pH and ANC to critical levels. Some of this depression in pH and ANC is a result of dilution of surface waters by snowmelt (Campbell and others 1995; Melack and Sickman 1995). Evidence of acidic episodes have been collected in lakes and streams of Shenandoah, Great Smoky Mountains, Rocky Mountain, Sequoia-Kings Canyon and Yosemite National Parks. Any class 1 area with low-ANC surface waters and a seasonal snowpack can experience episodes.

Unresolved Issues and Research Gaps

Why ANC Is Not Recovering in the East—It appears that the level of sulfur emission control required by the CAAA will not permit the most acidified lakes in regions like the Adirondacks (NY) to recover. There are questions about why this recovery is not occurring. Signs point to loss of base cations (calcium and magnesium) from the soils and the reduction of these same base cations in rainfall. Continued deposition and surface-water monitoring are needed, along with improved response models, before the "right" levels of deposition are identified. The Canadians are calling for another round of sulfur reductions, and possibly nitrogen oxide reductions, to permit the recovery of their sensitive lakes in the Eastern provinces (Environment Canada 1998).

Fate of Nitrogen in Ecosystems—The concept of "nitrogen saturation" of ecosystems was introduced in the late 1980s, at the close of NAPAP (Aber and others 1989). Because N is an essential nutrient for plant growth, it has been more difficult to determine why N is "leaking" out of systems all over the world. A number of stresses and natural processes, including fire, land use, disturbance and insect infestation, can cause the terrestrial systems to "leak" N to streams and lakes (Fenn and others 1998). In alpine regions of the Rockies, the extent of seasonal snow cover will influence the amount of N leaving the terrestrial system in the spring snowmelt (Williams and others 1996b). Even in the Northeast, where N loading is high, there is evidence that climate is an important control of N cycling (Mitchell and others 1996).

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, indicating that the supply of nitrogen has exceeded the capacity of the soils and vegetation to absorb it (Stoddard 1994). There are a number of explanations for this nitrogen "leakage," including the maturation of forests, effects of insect infestation and excess nitrogen supply in deposition. Recent investigations in Shenandoah National Park have attempted to separate out the effects of nitrogen flux to upland systems due to deposition from the impact of nitrogen cycle disruption from a gypsy moth infestations. At these affected watersheds, the export of nitrogen via streamwater has resulted in increased frequency of acidic episodes, known to affect native fish species (Bulger and others 1998).

In forests of the arid Southwest, recent data suggest that fire is the most important factor influencing the N cycle (Johnson and others 1998). Most of the forested areas in the West receive low to moderate N deposition, with the exception of southern California (Fenn and others 1996). Studies in Little Valley, Nevada indicate that N fluxes via fire and post-fire N-fixation greatly exceeded atmospheric deposition and leaching of N.

Because of these different controls on nitrogen cycling throughout class 1 areas, there is a need for continued monitoring and research to determine the role of deposition and to define "critical loads" or thresholds of N to protect ecosystem function.

Do We Have the Right Indicators for AQRVs?—Researchers are looking for the best "indicator" of ecosystem response to increasing inputs of S and N. We have moved past the concept of "dead lakes" and "dead fish" to consider what metrics should be used to determine the health of a sensitive system and its response over time to changes in deposition. There is a general acceptance that chemical endpoints, such as pH and ANC of streamwaters or the calcium/aluminum ratio in soil waters, have characteristics that make them good choices as indicators.

The next challenge is to tie changes in these chemical parameters to ecological processes or biological populations that people and land managers "care about," such as frogs, fish or spruce trees. The current state of science cannot make that connection, with the exception of the effects of acidification on fish populations. And even with the fish and acidification relationship, there are enough confounding factors, such as habitat quality, food supply, predation and competition, to make the dose/response relationship less than straightforward. The selection of sensitive indicators will also require that the species or ecosystem process have a predictable response to deposition, one not confounded by other environmental responses (Hacker and Neufeld 1993).

How to Explore Links Among Climate Change, UV Radiation and Regional and Global Pollutants—We tend to compartmentalize air quality effects research, when in reality, these stressors can interact to give us effects that we did not anticipate. One recent example is the interaction of climate, UV radiation and acid deposition in the boreal forest areas of Canada. Research on lakes indicates that acidity in deposition reduces the amount of dissolved organic matter in lakes, allowing UV radiation to penetrate deeper, thus increasing exposure to potentially sensitive aquatic biota, such as phytoplankton, fish and frogs larvae (Leavitt and others 1997; Schindler and others 1996; Yan and others 1996). Increases in temperature and incidence of drought can also affect the way that lakes, streams and wetlands respond to acidification, depending on local conditions.

Another unexpected finding was based on long-term data collected at a watershed study site in Olympic National Park, at the western edge of North America. It was assumed that this site would be "unaffected" by air pollution because of the lack of identifiable "upwind" sources. A recent intensive monitoring experiment (Jaffe and others, in press) and analysis of long-term precipitation and streamwater data at the Hoh Rainforest site in Olympic National Park (Edmonds and Murray 1999) suggest that dust and industrial air pollutants are being transported in the spring from the Asian continent to North America.

In both cases, these unexpected air pollution stressor interactions were discovered after analysis of long-term monitoring and effects data not necessarily collected for this purpose. These cases, among others, point to the importance of long-term data collection at intensive sites, especially in parks and wilderness areas that are relatively protected from changes in land use and local pollution (Herrmann and Stottlemyer 1991; Stottlemyer and others 1998).

Scaling Up to Landscapes and Bioregions—FLMs cannot do detailed research and monitoring in all class 1 areas. They need to be able to extrapolate both deposition loading and indicator responses based on information gathered at other sites and GIS-based extrapolation techniques. There have been a number of attempts to integrate point data and process information in the form of regional assessments of the effects of air pollutant on FLM resources. These include the Southern Appalachian Assessment (SAMAB 1996), the Inner Columbia River Basin study (Haynes and others 1998), the Southern Appalachian Mountains Initiative (SAMI 1999) and the Sierra Nevada Ecosystem Project (SNEP 1996). Building on watershed-based research and monitoring (Herrmann and Stottlemyer 1991) and network deposition estimates, and using effects models, FLMs can estimate impacts. Verification monitoring is essential to validate this use of models, such as MAGIC or NuCM. Such a GIS overlay of stressors and forest responses was used in assessing the effects of ozone on forests in the Southeast (Hogsett and others 1997). Another method of "scaling up" includes the use of remote sensing to estimate the regional distribution of resources, such as forest cover type.

Monitoring and Research Methods Appropriate for Wilderness—In keeping with the mandates of the Wilderness Act, most FLMs are reluctant to permit intrusive research and monitoring activity in parks and wilderness areas. There has been development of research and analysis methods that allow for extrapolation of monitored data collected at points outside of wilderness. Vertucci and Eilers (1993) describe a method of lake sampling that is less rigorous than the Western Lake Survey, but which does allow an FLM to "screen" potential AQRVs for sensitivity. There has also been use of passive air quality monitors that allow for extrapolation of data collected at more sophisticated monitoring stations outside of wilderness boundaries. Most importantly perhaps, the methods of drawing deposition isopleths and using models to estimate deposition along elevation gradients hold promise for estimating both the air pollution levels and indicator responses without extensive monitoring and manipulative research. Experiments to demonstrate dose/response relationships are often conducted on lands adjoining wilderness areas, where this activity is more appropriate.

How to Estimate Total Deposition—To apply critical loads approaches to protect AQRVs, it is necessary to calculate annual deposition loads of S and N to sensitive regions. To make these estimates, FLMs need to consider how to include information on dry deposition, snow, fog and cloudwater.

Snowpack monitoring is a method of estimating the total wet and dry loads to wilderness areas that does not require active samplers (Heuer and others 2000). There is long-term snowpack monitoring at a number of Western watershed sites, but only one regional snow deposition sampling network currently in place, the Rockies Dividewide Snow Survey along the Continental Divide in Montana, Wyoming, Colorado and New Mexico, carried out by the U.S. Geological Survey, in cooperation with the USDA-FS, State of Colorado and National Park Service (Ingersoll 1995). Since the spring of 1993, researchers have collected snowpack samples during the period of maximum snow accumulation to estimate the total loading during the period of approximately October to March. Synoptic snow monitoring projects in the western U.S. have provided estimates of regional solute deposition during the winter period along the Cascade and Sierra crest and throughout the Sierra Nevada (McGurk and others 1989).

Cloudwater and fogwater can contribute significantly to total loading of solutes in some parts of the U.S. in certain types of environments. In high-elevation areas of eastern North America, cloudwater impaction can account for an equivalent amount of loading of sulfate and nitrate as other forms of wet precipitation (for example, at Noland Divide in Great Smoky Mountains National Park, (Johnson and Lindberg 1992)). Research on cloudwater deposition has included limited years of monitoring by the Mountain Cloud Chemistry network (Vong and others 1991), and the CASTNet subnetwork, which collects samples at three high-elevation sites in the east during the summer: Clingman's Dome, Great Smoky Mountains National Park (TN/NC), Whitetop Mountain (VA) and Whiteface Mountain (NY). Measurements of cloudwater deposition in Western mountains have been confined to short-term research projects in the Sierra Nevada (Sequoia-Kings Canyon National Parks (CA)) and the Rockies (Mt. Werner (CO)). Because of the harsh monitoring environments, especially in winter, high-elevation cloudwater monitoring is not practical.

It is likely that experiments in measuring and modeling of deposition along elevational gradients in the both the East and the West will lead to methods of estimating total deposition, without the need to go to heroic lengths to measure all forms of deposition everywhere (Lovett and others 1999). Once the deposition models are developed, they can be used to estimate “total” deposition to sensitive environments.

Use of Research and Monitoring Results by Managers

The states and the EPA are the authorities that regulate emissions of deposition precursors, NO_x and SO_x. The FLMs can advise these agencies on the need to control pollution entering wilderness areas and parks. FLMs can intervene with EPA and the states under the National Environmental Policy Act to review environmental impact statements. They can also use existing data on air pollution and its effects in the review of State Implementation Plans and in the review of new source permits under the CAAA provisions for New Source Review (NSR). FLMs can also certify impairment to visibility caused by emissions from existing sources. Of primary importance to their strategy to prevent damage to AQRVs, FLMS need to provide information and education to regulators, the general public and the media as a way of calling attention to adverse impacts in parks and wilderness areas.

FLMs are often at the forefront of alerting the public and regulators of new air pollution threats to class 1 areas. The USFS and NPS were among the first to provide information on the role of N species in degrading visibility and affecting deposition quality in the Rocky Mountains. In parts of the West, N species in deposition can be equally weighted between nitrate (NO_3) and ammonium (NH_4). Ammonia (NH_3) emitted from agricultural operations, fertilizers, industrial operations (power plants and fertilizer manufacturing facilities) and animal feedlots are likely to contribute to the overall loading of N in locations, such as the western slope of the Sierra Nevada (Blanchard and others 1996) and the eastern slope of the Rockies (Heuer and others 2000). This issue came to the attention of air managers in Colorado through the efforts of the NPS and the USFS in discussions on the effects of nitrogen loading to Rocky Mountain National Park and wilderness areas of the Front Range (Williams and Tonnessen, in press; Williams and others 1996b).

The following discussion includes a number of specific cases where FLMs, through unilateral action or as members of affected groups, have used research and monitoring data to influence regulatory actions to clean up SO_x and NO_x emissions.

Progress in Managing Deposition

Adverse Impact Determinations—FLMs routinely use deposition monitoring data and effects information in permit reviews, part of their responsibility to “prevent significant deterioration” due to new sources. In only two cases has the NPS recommended that the states or the EPA declare “adverse impact” of air pollution on resources. In the 1980s, both Shenandoah National Park (VA) and Great Smoky Mountains National Park (TN/NC) were surrounded by proposed sources requesting permits, while existing deposition was already affecting streams and soils in these two class 1 areas (Shaver and others 1994). In both cases, the states disagreed with the NPS finding of “adverse impact,” and new source permits were granted. However, the data on effects were persuasive enough that the Southeastern states and EPA organized the Southern Appalachian Mountains Initiative (SAMI) as a forum for coming up with regional air pollution control strategies to protect class 1 areas (SAMI 1999).

The USFS also reviews new source permits for proposed emission sources near class 1 wilderness areas. The USFS has developed “screening documents” for different regions, ecosystems and regional pollutants of interest (Fox and others 1989). These reports provide guidance to the USFS on the levels of air pollutants likely to cause effects on terrestrial, aquatic and visibility resources within the national forest system. The USFS has applied the concept of level of acceptable change (LAC) to resources (Peterson and others 1992). This is similar to the concept of “adverse impact,” but sets numerical goals that serve as thresholds of damage to resources. For example, for aquatic resources in the Sierra Nevada, California, the USFS recommends that “significant deterioration” be considered likely with a long-term reduction of ANC of between 5-10 ueq/l (Peterson and others 1992). Threshold LAC values are based on an extensive literature on effects of pollutants on AQRVs.

Regional Air Quality Groups and Assessments—Discussions of regional air pollution impacts on visibility and other AQRVs have resulted in new experiments in regional air management. This is necessary to deal with air pollution transported to remote parks and wilderness areas, such as ozone, fine particles and acidic deposition. Under the Clean Air Act Amendments of 1990, Congress provided a general mechanism for dealing with interstate pollution problems, via section 176A. This section gives the EPA Administrator authority to create interstate transport commissions, “Whenever, on the Administrator’s own motions or by petition from the Governor of any state, the Administrator has reason to believe that the interstate transport of air pollutants from one or more states contributes significantly to a violation of a national ambient air quality standard in one or more other states, the Administrator may establish, by rule, a transport region for such pollutant that includes such states” (CAAA of 1990, section 176A).

The CAAA called for the creation of the Grand Canyon Visibility Transport Commission (GCVTC), a group of eight states and four tribes concerned with air quality in the southwestern U.S. This group completed their final report to the EPA in 1996 and recommended strategies to improve visibility on the Colorado Plateau. The commission further urged the EPA to create and fund a new Western air management group, known as Western Regional Air Partnership.

Another regional air consortium recently celebrated its seventh anniversary. The Southern Appalachian Mountains Initiative (SAMI) deals with effects on AQRVs from regional air pollutants transported to the 10 class 1 areas located in the eight SAMI states. This group was charged by the EPA with coming up with a comprehensive regional strategy to deal with air pollution issues affecting resources in the 10 class 1 areas. A final integrated assessment is expected in 2001.

It is likely that this approach to regional air management, with emphasis on class 1 areas, will continue and expand as we look for options to protect AQRVs in these areas, especially in light of the new regional haze rules promulgated by EPA to protect class 1 visibility. EPA is planning to fund two to four additional regional air management partnerships to help plan for restoration of natural background visibility throughout the U.S.

Controls on Existing Power Plants—Since the "visibility goal" was endorsed by Congress in the CAAA of 1977, there have been a number of attempts by FLMs to get Best Available Retrofit Technology (BART) on uncontrolled power plants. Special "attribution" studies were performed to link SO_2 and NO_x emissions to visibility impairment and other adverse impacts on AQRVs at the following parks and wilderness areas: Grand Canyon and Canyonlands National Parks affected by the Navaho Generating Station (National Research Council 1993); Mount Rainier Wilderness and Alpine Lakes Wilderness affected by Centralia Power Plant, Washington; Grand Canyon National Park and Glen Canyon National Recreation Area being affected by the Mohave Power Plant, Nevada (Green 1999); and the Mt. Zirkel Wilderness being affected by the Craig and Hayden Power plants, Colorado (Jackson and others 1996). In each case, with the exception of the Mohave Power Plant, which is still in negotiations, there was agreement to control emissions. However, in all of these cases, the effect of S and N deposition on ecological resources was not the deciding factor in the clean-up decision. However, there is no question that ecological systems in these affected parks and wilderness areas will benefit from the emission reductions.

What Managers Need

Long-Term Monitoring and Index Sites—The best way for FLMs to develop long-term databases on stressors and ecosystem responses is to participate in interagency programs that allow for leveraging of resources. The FLMs have the advantage of managing relatively "unaffected" sites where monitoring programs can operate without local disturbance or likely change in land use. FLMs should think of the parks, refuges and forest lands as "outdoor laboratories," where research and monitoring can be supported, often with in-kind services. There are existing networks of long-term environmental monitoring sites, many located adjacent to wilderness areas on national forests, parks and wildlife refuges.

The USFS has a network of experimental forests including, Fernow Experimental Forest (WV), Hubbard Brook Experimental Forest (NH), Fraser Experimental Forest (CO), H.J. Andrews Experimental Forest (OR) and Coweeta Experimental Forest (GA). The USFS is also host to a number of Long-Term Ecological Research sites (LTER), funded by the National Science Foundation. LTER sites include experimental forests, the Pawnee Grasslands and Niwot Ridge (CO). At these sites, outside of wilderness, extensive monitoring and research manipulations can be carried out, producing data that can be applied to wilderness area resources (Adams and others 1997).

In the coastal zone, there are a number of research sites maintained by NOAA and EPA, including the recently organized Coastal Index Site Network (CISNET) and the National Estuary Program (NEP). NPS units serve as sites for a number of long-term networks and index site networks, including the Prototype Parks Monitoring Program (NPS Inventory and Monitoring program funding); the small watersheds program (USGS funding) (Herrmann and Stottlemyer 1991); the Water, Energy, and Biogeochemical Budgets program (USGS); and the Park Research and Intensive Monitoring of Ecosystems Network (PRIMENet) (EPA and NPS funding) (Summers and Tonnessen 1998).

PRIMENet is the first project to be jointly funded by the EPA and the National Park Service to address the linkages between environmental stressors and ecosystem responses. PRIMENet is designed to monitor major environmental stressors, such as UV, air pollution, contaminants and climate and to relate changes in these stressors to ecological indicators at 14 parks, representing a range of ecosystems (Figure 7).

AQRV Inventories and Monitoring—FLMs are acutely aware that they do not have a good inventory of the natural resources on the lands they manage. The National Park Service realized that it was not carrying out the mandate to identify and then monitor the condition of their resources, as directed by Congress. The scope of the problem was laid out in articles by Stohlgren and others (1995); and Stohlgren and Quinn (1992). This realization led to funding of a long-term ecological monitoring program in the National Park Service, with the centerpiece of the program being a network of 22 "prototype parks" that develop monitoring protocols, in cooperation with the USGS, and then transfer these methods to other parks with similar ecosystems and landscape classification. A complement to the prototype parks program is funding for a comprehensive set of natural resource inventories for the more than 260 park units with resource concerns and issues. Resources to be inventoried are Air Quality-Related Values or sensitive indicators of air pollution.

Development and listing of sensitive AQRVs in class 1 areas is one of the tasks taken on by the Federal Land Managers Air Quality-Related Values Work Group (FLAG 1999). This effort by the USFS, FWS and NPS will continue into Phase 2 of the program.

Dose/Response Information—There are now well-developed methods and models to determine the amount of deposition needed to change surface-water chemistry. There are also a limited number of biological populations that have been tested for response to acidification in lakes and streams. Linking these different types of models was used to assess fish viability in Southeastern streams, using field data from the Shenandoah Watershed Study and the Virginia Trout Stream Sensitivity Study (Bulger and others 1998). The MAGIC model was used in this assessment to forecast the effects of different deposition scenarios on surface water quality. It is currently being modified and tested at watershed sites in parks and wilderness areas in the Rockies, the Sierra Nevada and the Cascades, with the expectation that this model will be used for regional assessment of class 1 areas in the West.

Dose/response data are harder to come by for terrestrial effects of deposition. The Nutrient Cycling Model (NuCM) was developed in the eastern U.S. to forecast the change in soil water chemistry, and indirectly to assess forest health, with different loadings of N and S. It was used in the

Southeast in the spruce-fir zone, the terrestrial system most under stress from deposition (Johnson and others 1996).

Biota that show responses in the lab and the field to acidification include zooplankton, stream invertebrates, fish and amphibians. Experiments to determine biological response to chronic or episodic acidification have been conducted in parks and national forests, including work at Emerald Lake in Sequoia-Kings Canyon National Park (CARB 1993). Zooplankton species, such as *Daphnia rosea*, were found at reduced levels in lakes that have experienced acidification (Barmuta and others 1990). Among the benthic invertebrates found in streams, the mayfly larva, *Baetis* spp., are adversely affected by acidic episodes (Kratz and others 1994). These two species are important as food items for native fish in high-elevation aquatic systems. Native fish species, such as cutthroat trout and rainbow trout, can be sensitive to acidic waters, depending on the life stage exposed to acidic episodes. In general, fish population viability is expected to be reduced below pH 6 (Baker and others 1990). Two amphibian studies conducted in the Rockies point to the direct effects on salamander eggs of acid episodes and possible community level responses of competing amphibian species. Harte and Hoffman (1989) exposed the eggs of tiger salamanders (*Ambystoma tigrinum*) to experimental increases in episodic acidification and determined that they had an LD-50 pH of 5.6, which is within the range of snowmelt pHs encountered in the Rocky Mountains. In a study of coexisting populations of tiger salamanders and chorus frogs (*Pseudacris triseriata*), Kiesecker (1996) reports that changes in development rates in these larvae can be effected by depressed pHs in pond water, leading to changes in predatory success.

It is not always practical for FLMs to conduct these costly experiments in all sensitive systems. The development of empirical models, along with the transfer of these models to similar ecosystems, is the only feasible method to allow for estimation of loss of biota with increasing acidification, although this approach is accompanied by uncertainty.

Critical Loads, Critical Levels, and Thresholds—Existing standards for air pollution (NAAQS) will not work to protect ecosystems and biota from deposition. Ambient concentrations in air do not translate well into deposition of N and S to watersheds, forests and estuaries. Therefore, we need to use the "critical loads" approach that has been developed by the Europeans and the Canadians. NAAQS may be considered as "critical levels" of pollutants that may affect human health or natural resources (Bull 1991). However, this kind of ambient gaseous or particle standard is aimed toward inhalation risk, rather than the risk of pollutant deposition effects on resources (such as N deposition effects on surface waters). It is likely that a more stringent PM-2.5 standard will reduce the load of particles transported into high-elevation regions and then deposited to sensitive resources via wet or dry deposition. However, this is not one of the major pathways considered in setting these standards.

Critical loads are deposition levels above which natural resources can be negatively affected. The European countries and Canada have been at the forefront of setting critical loads and target loads to protect their forests, soils, lakes and streams from deposition of S and N. The difference between these two levels can be explained in the policy context. Critical loads are the levels below which no effect to sensitive resources is expected; target loads are the amount of deposition that will result in an "acceptable level" of damage to resources. For example, Dise and Wright (1995) calculate that below a deposition rate of 10 kg/ha/yr of N, no significant nitrogen leaching should occur in European forests; above 25 kg/ha/yr, there is significant leaching. Therefore, 10 kg/ha/yr would be the critical load, and some value between that and 25 kg/ha/yr could be chosen at the target load. It should be noted that existing critical load values are site specific and based on intensive site investigations.

In the U.S., the CAAA of 1990, section 404, called for the EPA to prepare a report on the feasibility and the environmental effectiveness of setting an acid deposition standard to protective sensitive aquatic and terrestrial resources. The completed report includes a number of modeling analyses that project the effect of reductions in both S and N deposition in areas well studied during the National Acid Precipitation Assessment Program (U.S. EPA 1995). The conclusions of the EPA's analysis are that: (1) the uncertainties associated with effects of nitrogen on ecosystems are such that critical loads cannot be set at this time; (2) there had been no policy decision regarding the level of acceptable damage to systems; and (3) any critical load standards would have to be set on a regional basis and then enforced with regional pollution abatement strategies.

Some states have taken the lead in addressing transport and deposition of secondary pollutants, such as acid deposition and ozone. Minnesota is the only state that currently has an air quality standard to protect sensitive lakes from acid deposition. This state set a limit on total annual sulfate deposition of 11 kg/ha/year in order to keep the pH of precipitation above 4.7 to protect sensitive lakes (Orr and others 1991, 1992). The California legislature passed a statue called the "Atmospheric Acidity Protection Act," which called for a program of research and monitoring of acid deposition and atmospheric acidity in both urban and rural areas, with an assessment requirement (CARB 1995). The California Air Resources Board was to determine the need for an atmospheric acidity standard to protect both human health and natural systems. That determination has not been made to date.

Ability to Scale Up to Regional Systems—For a number of natural resource management issues, assessments need to be done on a bioregional basis because of the often contiguous management by different state, federal and private organizations. Air management is an issue that requires regional assessments. In the southeastern U.S., the FLMs collaborated, under the auspices of the Southern Appalachian Man in the Biosphere, to determine the condition of federal land resources in the Southeast. This Southern Appalachian Assessment included a report on regional air pollutants and their effects on class 1 resources (SAMAB 1996). It made use of GIS tools and extrapolation techniques for estimating the distribution of air pollutants, such as ozone and deposition, over the landscape. The Southern Appalachian Mountains Initiative (SAMI 1999) is performing a more detailed modeling and assessment exercise for the Southern Appalachian mountain regions, with a particular focus on eight states and the 10 class 1 areas within its boundaries: West Virginia: Dolly Sods and Otter Creek Wilderness Areas; Virginia: Shenandoah National Park and

James River Face Wilderness Areas; North Carolina: Shining Rock and Linville Gorge Wilderness Areas; North Carolina and Tennessee: Great Smoky Mountains National Park and Joyce Kilmer-Slickrock Wilderness Area; Georgia: Cohutta Wilderness Areas; Alabama: Sispey Wilderness Area; and the states of Kentucky and South Carolina, which have no class 1 areas located within the Southern Appalachian bioregion. The stressors of interest in this assessment include fine particles, ozone and acid deposition. An integrated modeling approach is being pursued, with final assessments of emission management options due in 2001.

There have been two bioregional science assessments performed in the West at the request of Congress: the Inner Columbia River Basin assessment (Haynes and others 1998) and the Sierra Nevada Ecosystem Project (SNEP 1996). The objective of these assessments was to determine to current status of natural resources and the trends in their condition, and to propose alternative strategies for land and resource management, using existing data organized with geographic information systems. The goal of the assessments was to balance the social and economic needs of the regions with the need to preserve ecosystem integrity on private, state and federal lands managed by the USFS, the NPS, FWS and the Bureau of Land Management. Both of these ecosystem assessments included an analysis of regional and local air pollution and the effects of these stressors on natural resources. Schoettle and others (1999) present an analysis of air resources for the ICRB region, which includes all or part of the states of Montana, Wyoming, Idaho, Washington, Oregon and a small slice of California and Nevada. The SNEP (1996) evaluated the Sierran bioregion, including parts of California and Nevada. The air issues identified as important in the Sierra Nevada included ozone injury to native tree species and the impairment of visibility due to fine particles from fossil fuel combustion, windblown dust, forest fires and residential wood burning. Although declines were noted in some fauna, such as the mountain yellow-legged frog, the array of stresses leading to loss of biodiversity in the Sierra is the subject of additional research and long-term monitoring.

In the Northern Hemisphere, there are three organizations that have performed assessments of transboundary air pollution. These include the trilateral Commission on Environmental Cooperation (CEC 1998), the International Air Quality Advisory Board of the International Joint Commission (IAQAB 1998) and the U.S./Canada Air Quality Committee. These groups have shown different levels of interest in class 1 area issues related to air pollution in the border region. The U.S./Canada Air Quality Committee, created under the U.S./Canada Air Quality Agreement to control acid rain in the two countries, is also active in planning for control of the other transboundary pollutants, such as fine particles and ozone, and submits biennial progress reports to the governments (U.S./Canada Air Quality Committee 1998).

Integrated Modeling—It is becoming more important to link models to allow regulators to forecast the results of emissions reductions on resources. To do "scenario testing," it is necessary to follow a proposed change in emissions as it translates into changes in deposition and then determine effects on ecosystems, visibility, human health and socioeconomic factors. There have been a number of efforts to do this model linkage, including the Canadian's use of RAISON model (Lam and others 1998), the NAPAP effort to develop and use the TAF (Tracking and Analysis Framework) (NAPAP 1998) and SAMI's development and testing of their own series of models, including MAGIC and NuCM for assessing effects on water chemistry and soil and forest health (SAMI 1999). Another step in ecological modeling has been used in an assessment of deposition effects on fish in the streams of the Virginia mountains. After "scenario testing" using MAGIC (Cosby and others 1985; Sullivan and Cosby 1995), Bulger and others (1998) linked projected water chemistry changes to changes in fish population status using an empirical model. A survey of other fish response models is available in Baker and others 1990. This is an important step—to link the water chemistry variables that we can measure in the field with a biological response that the public and land managers care about.

Information Management and Data Display Tools—With the vast array of data and information available for class 1 parks and wilderness areas, there is now a need for computer-based methods to organize, access and synthesize these data sets. The NPS, FWS and USFS all have projects ongoing to organize air monitoring and effects data. The NPS and FWS data management system is called AQUIMS (Air Quality Information Management System) (Nash and others 1996). All class 1 areas managed by the NPS and FWS are listed in the database, along with natural resource and air quality information. AQUIMS also includes annotated bibliographies on deposition and ozone. AQUIMS is now incorporated into a larger NPS data management system, known as SYNTHESIS. The USFS-Air Resource Management Program is developing an Air Module (NRIS-AIR) to link to the Natural Resource Information System. This system will incorporate a broad array of data collected by the USFS and cooperators for assessing air pollution effects on resources in national forests and grasslands.

Geographic information systems are useful tools for managers to access and organize these data. This tool has been used extensively in bioregional assessments, including the Southern Appalachian Assessment (SAMAB 1996), the Sierra Nevada Ecosystem Project (1996) and Inner Columbia River Basin Assessment (Haynes and others 1998).

Decision Support and Expert Systems—It is not enough to organize and display data on air pollution levels and indicator responses. FLMs need interpretation and "expert" judgment to understand how pollutants may be injuring resources. Decision-support systems, or "expert systems," provide this type of interpretation of data. The NPS and FWS are developing an interactive expert systems module in AQUIMS to interpret deposition and ozone effects information (Nash and others 1997). The deposition module, developed with input from a team of experts on aquatic and terrestrial effects, will allow FLMs to input existing surface water quality data for lakes and streams to determine: (1) current acidification status, (2) likely cause of high concentrations of acid anions (SO_4 or NO_3), (3) sensitivity of waters to increases in N or S deposition, and (4) display the results on a GIS that color-codes acidification states of fresh water in the class 1 area.

FLM Strategies

FLMs alone cannot control air pollution transported to parks or wilderness areas. They are required to work with a myriad of interests outside their borders to control local, regional, hemispheric and global air pollution. Some possible options for FLMs to join the larger community of "stakeholders" to protect class 1 resources and scenic values include:

1. Participating in regional air assessment groups and partnerships (such as WRAP, SAMI).
2. Alerting the public to resource threats through education and interpretive programs and "leading by example" in cleaning up sources of air pollution with the park or wilderness area.
3. Advising regulators on levels of air pollution that can affect sensitive AQRVs, e.g., NAAQS, critical loads and levels and threshold of injury.
4. Attracting research and monitoring funds and good research groups to conduct targeted studies in class 1 areas, or similar reserves where data can be extrapolated.
5. Assisting in the collection of air quality and AQRV data to protect resources from transported fine particles, ozone and deposition; this includes providing scientific infrastructure and access for research groups to research sites in parks, wildernesses, or adjacent lands.
6. Making information available to the public via websites (Table 2).

Table 2—Air quality websites.

National Park Service, Air Resource Division
http://www.nature.nps.gov/ard

PRIMENet
http://www.forestry.umt.edu/primenet

USFWS/Air Quality Branch
http://www2.nature.nps.gov/ard/fws/fwsaqb.htm

USDA-FS, National Air Resource Management
http://www.fs.fed.us/r6/aq/natarm

Environmental Protection Agency, Office of Air
http://www.epa.gov/oar

Regional Haze Rules, EPA-OAQPS
http://www.epa.gov/ttn/oarpg

Western Regional Air Partnership (WRAP)
http://www.wrapair.org

Environmental Protection Agency, Deposition to estuaries
http://www.epa.gov/owow/oceans/airdep

US Geological Survey, Acid Rain Program
http://bqs.usgs.gov/acidrain

NTN/NADP Program
http://nadp.sws.uiuc

Mercury Deposition Network
http://nadp.sws.uiuc/mdn

CASTNet Program
http://www.epa.gov/ardpublic/acidrain/castnet

IMPROVE Program (optical data)
ftp://alta_vista.cira.colostate.edu

NAPAP Assessment
http://www.nnic.noaa.gov/CENR/NAPAP/NAPAP_96.htm

U Georgia National UV Monitoring Center
http://oz.phyast.uga.edu

EPA UV Monitoring Site
http://www.epa.gov/uvnet

Interagency UV Monitoring Site
http://www.arl.noaa.gov/research/programs/uv.html

References

Aber, J.D.; Nadelhoffer, K.J.; Steudler, P.; Melillo, J.M. 1989. Nitrogen saturation in northern forest ecosystems: excess nitrogen from fossil fuel combustion may stress the biosphere. BioScience 39: 378-386.

Adams, M.B; Angradi, T.R.; Kochenderfer, J.N. 1997. Stream waters and soil solution responses to 5 years of nitrogen and sulfur addition at the Fernow Experimental Forest, West Virginia. Forest Ecology and Management 95: 79-91.

Adams, M.B.; Nichols, D.S.; Federer, C.A.; Jensen, K.F.; Parrott, H. 1991. Screening Procedure to Evaluate Effects of Air Pollution on Eastern Region Wildernesses Cited as Class I Air Quality Areas. General Technical Report NE-151. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Radnor, Pennsylvania.

Barmuta, L.; Hamilton, S.; Cooper,S.; Kratz, K.; Melack, J. 1990. Responses of zooplankton and zoobenthos to experimental acidification in a high-elevation lake (Sierra Nevada, California, U.S.A.) Freshw. Biol. 23, 571-586.

Bales, R.; Davis,R.; Williams M. 1993. Tracer release in melting snow—diurnal and seasonal patterns. Hydrological Processes 7: 389-401.

Baker, J.P.; Bernard, D.P.; Christensen, S.W.; and others. 1990. Biological effects of changes in surface water acid-base chemistry, NAPAP Report 13. In: National Acid Precipitation Assessment Program, Acidic Deposition. State of Science and Technology Vol. II. 381 p.

Barnard, J.; Lucier, J. 1990. Changes in forest health and productivity in the United States and Canada. State of Science and Technology Report 16. National Acid Precipitation Assessment Program, Washington, D.C.

Binkley, D.; Giardina, C.; Dockersmith,I.; Morse, D.; Scruggs, M.; Tonnessen, K. 1997. Status of air quality and related values in Class I National Parks and Monuments of the Colorado Plateau. U.S. Department of the Interior, National Park Service, Air Resources Division, Denver, Colorado.

Blais, J.M.; Schindler, D.W.; Muir, D.; Kimpe, L.; Donald, D.; Rosenberg, B. 1998. Accumulation of persistent organochlorine compounds in mountains of western Canada. Nature 395: 585-588.

Blanchard, C.; Michaels, H.; Tanenbaum, S. 1996. Regional estimates of acid deposition fluxes in California for 1985-1994. Final Report. Contract 93-332. California Air Resources Board, Sacramento, CA.

Blanchard, C.; Tonnessen, K.A. 1993. Precipitation-chemistry measurements from the California Acid Deposition Monitoring Program, 1985-1990. Atmospheric Environment 27A: 1755-1763.

Bradford, D.F.; Swanson,C.; Gordon, M. 1994. Effects of low pH and aluminum on amphibians at high elevation in the Sierra Nevada, California. Can. J. Zool. 72: 1272-1279.

Brooks, P.; Williams, M.; Schmidt, S. 1996. Microbial activity under alpine snowpacks, Niwot Ridge, Colorado. Biogeochemistry 32: 93-113.

Brosset, C; Lord, E. 1991. Mercury in precipitation and ambient air: a new scenario. Water, Air and Soil Pollution 56: 493-506.

Bulger, A.; Cosby, J.; Webb, R. 1998. Acid Rain: Current and projected status of coldwater fish communities in the Southeastern U.S. In: The context of continued acid deposition. Trout Unlimited, Arlington, VA. 28 p.

Bull, K.R. 1991. The critical loads/levels approach to gaseous pollutant emission control. Environ. Pollut. 69: 105-123.

Bunyak, J. 1993. Permit application guidance for new pollution sources. Natural Resources Report NPS/NRAQD/NRR-93. U.S. Department of the Interior, National Park Service, Air Quality Division, Denver, Colorado.

California Air Resources Board (CARB). 1993. The Atmospheric Acidity Protection Program: Annual report to the Governor and Legislature, 1992. Sacramento, California.

Campbell, D.H.; Clow, D.W.; Ingersoll, G.P.; Mast, M.A.; Spahr, N.E.; Turk, J.T. 1995. Processes controlling the chemistry of two snowmelt-dominated streams in the Rocky Mountains. Water Resources Research 31(11): 2811-2821.

Chappelka, A.H.; Samuelson, L.J. 1998. Ambient ozone effects on forest trees of the eastern United States. New Phytologist 139: 91-108.

Charles, D. (ed). 1991. Acid deposition and aquatic ecosystems, Regional case studies. Springer-Verlag, New York.

Colborn, T.; Clement, C. (eds). 1992. Chemically-induced alteration in sexual and functional development: the human-wildlife connection. Princeton, NJ: Princeton Scientific Publishing Co., Inc.

Commission for Environmental Cooperation (CEC). 1998. Continental pollutant pathways: an agenda for cooperation to address long-range transport of air pollution in North America. Commission for Environmental Cooperation, Montreal, Canada.

Committee on Environment and Natural Resources (CENR). 1997. Integrating the Nation's environmental monitoring and research networks and programs: a proposed framework. National Research and Technology Council, Washington, DC.

Cosby, B.J.; Norton, S.A.; Kahl, J.S. 1996. Using a paired-watershed manipulation experiment to evaluate a catchment-scale biogeochemical model. Science of the Total Environment 183: 49-66.

Cosby, B.J.; Wright, R.F.; Gjessing, E. 1995b. An acidification model (MAGIC) with organic acid evaluated using whole-catchment manipulations in Norway. Journal of Hydrology 170: 101-122.

Dise, N.; Wright, R.F. 1995. Nitrogen leaching from European forests in relation to nitrogen deposition. Forest Ecology and Management 71: 153-161.

Dixon, L.K.; Esteves, E.D. 1998. Chassahowitzka National Wildlife Refuge—Status and Trends. In: NADP Technical Committee Meeting, Abstracts of Papers, St. Petersburg, FL: 55.

Eager, C.; Adams, M.B.(eds). 1992. Ecology and decline of red spruce in the Eastern United States. Springer-Verlag, New York. 417 p.

Edmonds, R.L.; Murray, G.L.D. 1999. Suspected asian dust influences stream chemistry in an old-growth ecosystem in the Hoh River Valley. (Abstract) Ninth Annual Review, Center for Streamside Studies, University of Washington, Seattle.

Eilers, J. M.; Rose, C.L.; Sullivan, T.J. 1994. Status of air quality and effects of atmospheric pollutants on ecosystems in the Pacific Northwest Region of the National Park Service. Technical Report NPS/NRAQD/NRTR-94/160. U.S. Department of the Interior, National Park Service, Air Quality Division. Denver, Colorado.

Eilers, J.M.; Brakke, D.F.; Landers, D.H.; and Kellar, P.E.; 1988. Characteristics of lakes in mountainous areas of the western United Stated. Verh. Int. Verein. Limnol. 23: 144-151.

Elder, K.; Dozier, J.; Michaelsen, J. 1991. Snow accumulation and distribution in an alpine watershed. Water Resources Research 27: 1541-1552.

Eldred. R.A.; Cahill, T.A. 1994. Trends in elemental concentrations of fine particles at remote sites in the United States of America. Atmospheric Environment 28 (5): 1009-1019.

Engle, D.; Melack, J. 1995. Zooplankton of high elevation lakes of the Sierra Nevada, California: potential effects of chronic and episodic acidification. Arch. Hydrobiol. 133: 1-21.

Environment Canada, 1998. 1997 Canadian acid rain assessment, Volume 1, Summary of results. Ministry of the Environment, Ottawa, Canada.

Federal Land Managers' Air Quality Related Values Work Group (FLAG). 1999. Phase 1 Report, (Draft), Lakewood, CO.

Fenn, M.; Poth, M.; Aber, J.; Baron,J.; Bermann, B.; Johnson, D.; Lemly, A.; McNulty, S.; Ryan, D.; Stottlemyer, R. 1998. Nitrogen excess in North American ecosystems: a review of geographic extent, predisposing factors, ecosystem responses, and management strategies. Ecological Applications 8: 706-733.

Fenn, M.E.; Poth, M.A.; Johnson, D.W. 1996. Evidence for nitrogen saturation in the San Bernardino Mountains in southern California. Forest Ecology and Management 82: 211-230.

Fox, D.G., A.M. Bartuska, J.G. Byrne, E. Cowling, R. Fisher, G.E. Likens, S.E. Lindberg, R.A. Linthurst, J. Messer and D.S. Nichols. 1989. A screening procedure to evaluate air pollution effects on Class I Wilderness Areas. General Technical Report RM-168. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado.

Grand Canyon Visibility Transport Commission. 1996. Recommendations for improving western vistas. Report of the Grand Canyon Visibility Transport Commission to the U.S. Environmental Protection Agency. 91 p.

Green, M. 1999. The project MOHAVE tracer study: study design, data quality, and overview of results. Atmospheric Environment 33: 1955-1968.

Groisman, P.Y.; Karl, T.R.; Knight, R.W. 1994. Changes of snow cover, temperature and radiative heat balance over the Northern Hemisphere. Journal of Climate 7: 1633-1656.

Hacker, W.D.; Neufeld, H.S. 1993. The false positive in bioindicators of air pollution. J. of Arboriculture 18: 249-250.

Haddow, D.; Musselman,R.; Blett, T.; Fisher, R. 1998. Guidelines for evaluating air pollution impacts on wilderness within the Rocky Mountain Region: Report of a Workshop, 1990. General Technical Report RMRS-GTR-4. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Ft. Collins, Colorado.

Harte, J.; Hoffman, E. 1989. Possible effects of acid deposition on a Rocky Mountain population of the tiger salamander, *Ambystoma tigrinum*. Conservation Biology 3: 149-158.

Haynes, R.W.; Graham, R.T.; Quigley, T.M. 1998. A framework for ecosystem management in the Interior Columbia Basin. Journal of Forestry 96 (10): 4-9.

Hedin, L.O.; Likens, G.E. 1996. Atmospheric dust and acid rain. Scientific American 275(6): 88-92.

Hedin, L.O.; Granat, L.; Likens, G.E.; Buishand, T.A.; Galloway, J.N.; Butler, T.J.; Rohde, H. 1994. Steep declines in atmospheric base cations in regions of Europe and North America. Nature 367: 351-354.

Herrmann, R.; Stottlemyer, R. 1991. Long-term monitoring for environmental change in U.S. National Parks: a watershed approach. Environmental Monitoring and Assessment 17: 51-65.

Heuer, K.; Tonnessen, K.; Ingersoll, G. 2000. Comparison of precipitation chemistry in the Central Rocky Mountains, Colorado, USA. Atmospheric Environment 34: 1713-1722.

Hogsett, W.E.; Weber, J.E.; Tingey, D.; Herstrom, A.; Lee, E.H.; Laurence, J.A.. 1997. An approach for characterizing tropospheric ozone risk to forests. Environmental Management 21 (1): 105-120.

Ingersoll, G. 1995. Maximum-accumulation snowpack chemistry at selected sites in northwestern Colorado during spring 1994. U.S. Geological Survey, Open File Report 95-139, Denver, CO.

International Air Quality Advisory Board (IAQAB). 1998. Special Report on Transboundary Air Quality Issues. International Joint Commission, Windsor, Ontario.

Jaffe, D.; Anderson, T.; Covert, D.; Kotchenruther, R.; Trost, B.; Danielson, J.; Simpson, W.; Berntsen, T.; Karlsdottir, S.; Blake, D.; Harris, J.; Carmichael, G.; Uno.I. Transport of asian air pollution to North America. Geophysical Research Letters (in press).

Jackson, L.; Geiser, L.; Blett, T.; Gries, C.; Haddow, D. 1996. Biogeochemistry of lichens and mosses in and near Mt. Zirkel Wilderness, Routt National Forest, Colorado: influences of coal-fired power plant emissions. Open File Report 96-295. U.S. Department of the Interior, U.S. Geological Survey.

Johnson, D.W.; Susfalk, R.B.; Dahlgren, R.A.; Klopatek, J.M. 1998. Fire is more important than water for nitrogen fluxes in semi-arid forests. Environmental Science and Policy 1: 79-86.

Johnson, D.W.; Susfalk, R.B.; Brewer, P.F. 1996. Simulated responses of red spruce forest soils to reduced sulfur and nitrogen deposition. Journal of Environmental Quality 25: 1300-1309.

Johnson, D.W.; Lindberg, S.E.(eds). 1992. Atmospheric deposition and forest nutrient cycling: a synthesis of the integrated forest study. Springer-Verlag, New York. 707 p.

Johnson, D.W.; van Miegroet, H.; Lindberg, S.E.; Todd, D.E.; Harrison, R.B. 1991. Nutrient cycling in red spruce forests of the Great Smoky Mountains. Can. J. For. Res. 21: 769-787.

Kendall, C.; Campbell, D.H.; Burns, D.A.; Shanley, J.B.; Silva, S.R.; Chang, C.C.Y. 1995. Tracing sources of nitrate in snowmelt runoff using the oxygen and nitrogen isotopic compositions of nitrate. In: Tonnessen, K.A.; Williams, M.W.; Tranter, M. (eds), Biogeochemistry of seasonally-covered catchments. IAHS Publ. No. 228: 339-347.

Kiesecker, J. 1996. pH-mediated predator-prey interactions between *Ambystoma tigrinum* and *Pseudacris triseriata*. Ecological Applications 6 (4): 1325-1331.

Kratz, K.; Cooper, S.; Melack, J. 1994. Effects of single and repeated experimental acid pulses on invertebrates in a high altitude Sierra Nevada stream. Freshwater Biology 32: 161-183.

Lam, D.C.L.; Puckett, K.J.; Wong, I.; Moran, M.D.; Fenech, G.; Jeffries, D.S.; Olson, M.P.; Whelpdale, D.M.; McNicol, D.; Marian, Y.K.G.; Minns, C.K. 1998. An integrated acid rain assessment model for Canada: from source mission to ecological impact. Water Qual. Res. J. Canada 33: 1-17.

Landers, D.; Gubala, C.; Verta, M.; Lucotte, M.; Johansson, K.; Vlasova; and Lockhart, W.L. 1998. Using lakes sediment mercury flux ratios to evaluate the regional and continental dimensions of mercury deposition in arctic and boreal ecosystems. Atmospheric Environment 32 (5): 919-928.

Landers, D.; Eilers, J.; Brakke, D.; Overton, W.; Kellar, P.; Silverstein, P.; Schonbrod, R.; Crowe, R.; Linthurst, R.; Omernik, J.;Teague, S.; Meier, E. 1987. Characteristics of lakes in the western United States, volume I, population descriptions and physio-chemical relationships. EPA/600/3-86/54a. U.S. Environmental Protection Agency, Washington, D.C. 176 p.

Lawrence, G.; Huntington, T. 1999. Soil-calcium depletion linked to acid rain and forest growth in the eastern United States. USGS Report WRIR 98-4267. February 1999.

Lear, G.; Frank, N. 1998. The long, dry road to total deposition: discovering EPA's Clean Air Status and Trends Network. In: NADP Technical Committee Meeting, Abstracts of Papers, St. Petersburg, FL: 19.

Lefohn, A.; Shadwich, D.S.; Somerville, M.C. [and others]. 1992. The characterization and comparison of ozone exposure indices used in assessing the response of loblolly pine to ozone. Atmospheric Environment 26A: 287-298.

Leavitt, P.R.; Vinebrooke, R.D.; Donald, D.B.; Smol, J.P.; Schindler, D.W. 1997. Past ultraviolet radiation in lakes derived from fossil pigments. Nature 388: 457-459.

Lovett, G.M.; Thompson, A.W.; Anderson, J.B.; Bowser, J.J. 1999. Elevational patterns of sulfur deposition at a site in the Catskill Mountains, New York. Atmospheric Environment 33: 617-624.

Lynch, J.; Bowersox, V.; Grimm, J. 1996. Trends in Precipitation Chemistry in the United States, 1983-94: an Analysis of the effects in 1995 of Phase I of the Clean Air Act Amendments of 1990, Title IV. Open-File Report 96-0346. U.S. Department of the Interior, U.S. Geological Survey.

Lynch, J.; Bowersox, V.; Grimm, J. 1995. Trends in precipitation chemistry in the United States: a national perspective, 1980-1992. Atmospheric Environment 29: 1231-1246.

Madronich, S. 1993. The atmosphere and UV-B radiation at ground level. In: Environmental UV Photobiology. Plenum Press, NY. 1993.

Malm, W. 1992. Characteristics and origins of haze in the continental United States. Earth Science Reviews 33: 1-36.

McGurk, B.; Berg, N.; Marks,D.; Melack, J.; Setaro, F. l989. Monitoring atmospheric deposition in California's Sierra Nevada: a comparison of methods. International Assoc. Hydrological Sciences, Publ #179: 71-79.

Melack, J.; Sickman, J. 1995. Snowmelt-induced chemical changes in seven streams in the Sierra Nevada. In: Tonnessen, K.A.; Williams, M.W.; Tranter, M. (eds), Biogeochemistry of seasonally snow-covered basins. IAHS Publication 228. International Association of Hydrological Sciences, Wallingford, UK, 1995: 221-234.

Miller, P.R.; Stolte, K.W.; Duriscoe, D.M; Pronos, J. 1996. Evaluating ozone air pollution effects on pines in the western United States. General Technical Report PSW-GTR-155. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Albany, California.

Mitchell, M.; Driscoll, C.T.; Kahl, J.S.; Likens, G.E.; Murdoch, P.S.; Pardo, L.H. 1996. Climatic control of nitrate loss from forested watersheds in the northeast United States. Environmental Science and Technology 30: 2609-2612.

Myneni, R.B.; Keeling, C.D.; Tucker, C.J.; Ashrar, G.; Nemani, R.R. 1997. Increased plant growth in the northern high latitudes from 1981-1991. Nature 386: 698-702.

Nash, B.L.; Tonnessen, K.A.; Heuer, K.H.; Davis, D.D.; Saunders, M.C.; Miller, B.J. 1997. Using the AQUIMS air quality decision support system to identify natural resources at risk from air pollution. Proc. of the Amer. Society for Photogrammetry and Remote Sensing, Seattle, WA: 362-369.

Nash, B.L.; Saunders, M.C.; Miller, B.J.; Tonnessen, K.A.; Davis, D.D.; and others. 1996. AQUIMS: a computerized system for interpreting and integrating information on air pollution effects on natural resources. Proc. of Eco-Informa '96; Lake Buena Vista, FL: 575-580.

National Atmospheric Deposition Program (NADP). 1999. NADP: 1997 wet deposition maps. Illinois State Water Survey, Champaign, IL.

National Acid Precipitation Assessment Program (NAPAP). 1991. Acid deposition: state of science and technology. Summary Report of the U.S. NAPAP. Washington, D.C.

National Acid Precipitation Assessment Program (NAPAP). 1998. NAPAP biennial report to Congress: an integrated assessment. National Science and Technology Council, CENR, Silver Spring, MD, May 1998.

National Research Council. 1993. Protecting visibility in National Parks and wilderness areas. Washington, D.C.: National Academy Press. 446 p.

Neufeld, H.S.; Lee, E.H.; Renfro, J.R.; Hacker, W.D.; Yu, B-H. 1995. Sensitivity of seedlings of black cherry (*Prunus serotina* Ehrh.) to ozone in Great Smoky Mountains National Park: I Exposure-response curves for biomass. New Phytologist 130: 447-459.

Orr, E.; Swain, E.; Strassman, R; Bock, D. 1991. Sulfur emissions and deposition in Minnesota: 1990 biennial report to the Legislature. Air Quality Division, Minnesota Pollution Control Agency, St. Paul, MN. 23 pp.

Orr, E.J.: Strassman, R.L; Swain, E.B. 1992. Minnesota wet sulfate deposition standard: 1991 compliance report. Air Quality Division, Minnesota Pollution Control Agency. St. Paul, Minnesota.

Peterson, D.L.; Schmoldt, D.L.; Eilers, J.; Fisher, J.; Doty, R. 1993. Guidelines for evaluating air pollution impacts on Class I Wilderness Areas in California. General Technical Report PSW-GTR-136. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Albany, California.

Peterson, D.L.; Sullivan, T.J.; Eilers, J.M.; Brace, S.; Horner, D.; Savig, K. 1998. Assessment of air quality and air pollutant impacts in National Parks of the Rocky Mountains and Northern Great Plains. U.S. Department of the Interior, National Park Service, Air Resources Division, Denver, CO.

Peterson, J.; Schmoldt, D.; Peterson, D.; Eilers, J.; Fisher, R.; Bachman, R. 1992. Guidelines for evaluating air pollution impacts on Class I Wilderness Areas in the Pacific Northwest. General Technical Report PNW-GTR-299. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, Oregon.

Porter, E. 1996. Air quality and air quality related values in Chassahowitzka National Wildlife Refuge and Wilderness Area. U.S. Fish and Wildlife Service, Air Quality Branch. Denver, Colorado.

Schindler, D.W.; Curtis, J.P.; Parker, B.R.; Stainton, M.P. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. Nature 379: 705-708.

Schoettle, A.; Tonnessen, K.; Turk, J.; Vimont, J.; Amundson, R.G. 1999. An assessment of effects of human-caused air pollution on resources within the Interior Columbia River Basin. General Technical Report PNW-GTR-447. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Seinfeld, J.H., 1989. Urban air pollution: state of science. Science 243: 745-762.

Shaver, C; Malm, W. 1996. Air quality in Grand Canyon. In: Halvorsen, W.L.; Davis, G.E. (eds). Science and ecosystem management in the National Parks. University of Arizona Press, Tucson, AZ: 227-250.

Shaver, C.; Tonnessen, K.; Maniero, T.M. 1994. Clearing the air at Great Smoky Mountains National Park. Ecological Applications 4: 690-701.

Sickman, J.; Melack, J. 1998. Nitrogen and sulfate export from high elevation catchments of the Sierra Nevada, California. Water, Air, and Soil Pollution 105: 217-226.

Sierra Nevada Ecosystem Project (SNEP). 1996. Summary of the Sierra Nevada Ecosystem Project Report. Centers for Water and Wildland Resources, Davis, CA.

Sisler, J.F.; Malm, W.C.; Gebhart, K.A.; Pitchford, M.L. 1996. Spatial and seasonal patterns and long term variability of the composition of the haze in the United States: an analysis of data from the IMPROVE Network. ISSN No. 0737-5352-32. Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado.

Southern Appalachian Man and the Biosphere Cooperative (SAMAB). 1996. The Southern Appalachian assessment: Atmospheric Technical Report. USDA-Forest Service. July 1996.

Southern Appalachian Mountains Initiative (SAMI). 1999. SAMI, 1999 Interim Report. SAMI, Asheville, NC. April 1999.

Stanford, J.; Acheson, A.; Brakke, D.; Eversman, D.; Savig, K.; Eilers, J. 1991. A screening procedure to evaluate air pollution effects in Region 1 wilderness areas, 1991. General Technical Report RM-GTR-294. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. Ft. Collins, Colorado.

Stoddard, J. 1995. Episodic acidification during snowmelt of high elevation lakes in the Sierra Nevada Mountains of California. Water, Air and Soil Pollution 85: 353-358.

Stoddard, J. 1994. Long-term changes in watershed retention of nitrogen: its causes and aquatic consequences. In: L.A. Baker. Environmental chemistry of lakes and reservoirs. Advances in Chemistry Series No. 237. American Chemical Society, Washington, D.C: 223-284.

Stoddard, J.L.; Driscoll, C.T.; Kahl, J.S.; Kellogg, J.H. 1998. Can site-specific trends be extrapolated to a region? An acidification example for the northeast. Ecological Applications 8(2): 288-299.

Stohlgren, T.J.; Quinn, J.F.; Ruggiero, M.; Waggoner, G.S. 1995. Status of biotic inventories in US National Parks. Biological Conservation 71: 97-106.

Stohlgren, T.J.; Quinn, J.F. 1992. An assessment of biotic inventories in western U.S. National Parks. Natural Areas Journal 12 (3): 145-153.

Stottlemyer, R; Toczydlowski, D.; and Herrmann, R. 1998. Biogeochemistry of a mature boreal ecosystem: Isle Royale National Park, Michigan. Scientific Monograph NPS/NRUSGS/NRSM-98/01. U.S. Department of the Interior, Denver, CO.

Summers, K; Tonnessen, K. 1998. Linking monitoring and effects research: EMAP's intensive site network program. Environmental Monitoring and Assessment 51: 369-380.

Sullivan, T.J.; Cosby, B.J. 1995. Testing, improvement and confirmation of a watershed model of acid-base chemistry. Water, Air and Soil Pollution 85: 2607-2612.

Sweet, C.W.; Prestbo, E.; Burnette, R. 1998. Wet deposition of total mercury at Mercury Deposition Network (MDN) sites in 1996 and 1997. In: NADP Technical Committee meeting, abstracts of papers, St. Petersburg, FL, October 26-29, 1998.

Tevani, M. (ed). 1992. UV-B radiation and ozone depletion: effects on humans, plants, microorganisms, and materials. Lewis Publishers, Boca Raton, FL.

Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie and E. Siemann. 1997. The influence of functional diversity and composition on ecosystem processes. Science 277: 1300-1302.

Turk, J.; Campbell, D. 1987. Estimates of acidification of lakes in the Mount Zirkel Wilderness Area, Colorado. Water Resources Research 23: 1757-1766.

Turner, R. S.; Fox, D.G; Bartuska, A; Jackson, W.; Bayle, B. Draft. Screening procedures to evaluate effects of air pollution on Forest Service wilderness in the Southern Region.

U.S./Canada Air Quality Committee. 1998. U.S./Canada Air Quality Agreement, 1998 Progress Report. U.S. Government Printing Office, Washington, D.C.

U.S. EPA. 1998. National air quality and emissions trends report, 1997. EPA 454-R-98-016. Office of Air Quality Planning and Standards, Research Triangle Park, N.C.

U.S. EPA. 1997. Deposition of air pollutants to the Great Waters. Second Report to Congress. Washington, D.C.

U.S. EPA. 1996a. Review of national ambient air quality standards for ozone: Assessment of scientific and technical information. OAQPS Staff Paper. EPA-452/R-96-007. U.S. EPA, Office of Air Quality Planning and Standards. Research Triangle Park, NC.

U.S. EPA. 1996b. Air quality criteria for ozone and related photochemical oxidants. Vol. 2. EPA/600/P-93/004bF. U.S. EPA, Office of Research and Development, Research Triangle Park, NC.

U.S. EPA. 1995. Acid deposition standard feasibility study: final report to Congress. EPA/430-R-95-001a. Washington, D.C. 120 p.

U.S. EPA. 1994. The EPA Great Waters program: an introduction to the issues and the ecosystems. EPA-453/B-94/030. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Durham, NC.

van Miegroet, H.; Johnson, D.W.; Cole, D.W. 1992. Analysis of N cycles in polluted versus unpolluted environments. In: Johnson, D.W.; Lindberg, S.E. (eds). Atmospheric deposition and forest nutrient cycling: a synthesis of the integrated forest study. Springer-Verlag, New York: 199-202.

Vertucci, F.A.; Eilers, J.M. 1993. Issues in monitoring wilderness lake chemistry: a case study in the Sawtooth Mountain, Idaho. Environmental Monitoring and Assessment 28: 277-294.

Vitousek, P.M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.; Schindler, D.W.; Schlesinger, W.H.; Tilman, D.G. 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological Applications 7(3): 737-750.

Vong, R.J.; Sigmon, J.T.; Mueller, S.F. 1991. ES&T Critical Review: Cloudwater deposition to Appalachian forests. Environmental Science and Technology 25: 1014-1021.

Wedin, D.A.; Tilman, D.G. 1996. Influence of nitrogen loading and species composition on the carbon balance of grasslands. Science 274: 1720-1723.

Wigington, P.J.; DeWalle, D.R.; Murdoch, P.S.; Kretser, W.A.; Simonin, H.A.; Van Sickle, J.; Baker, J.P. 1996. Episodic acidification of small streams in the northeastern United States: ionic controls of episodes. Ecological Applications 6(2): 389-407.

Wigington, P.J.; Davies, T.D.; Tranter, M.; Eshleman, K. 1990. Episodic acidification of surface waters due to acidic deposition. State of Science and Technology Report 12. National Acid Precipitation Assessment Program, Washington, D.C.

Williams, M.W.; Brooks, P.; Mosier, A.; Tonnessen, K.A. 1996a. Mineral nitrogen transformations in and under seasonal snow in a high-elevation catchment in the Rocky Mountain, United States. Water Resources Research 32: 3161-3171.

Williams, M.W.; Baron, J.; Caine, N.; Sommerfeld, R.; Sanford, R. 1996b. Nitrogen saturation in the Colorado Front Range. Environmental Science and Technology 30: 640-646.

Williams, M.W.; Bardsley, T.; Rikkers, M. 1998. Overestimation of snow depth and inorganic nitrogen wetfall using NADP data, Niwot Ridge, Colorado. Atmospheric Environment 32: 3827-3833.

Williams, M.W.; Tonnessen, K.A.. Setting critical loads for inorganic nitrogen deposition in the Colorado Front Range, USA. Ecological Applications. (in press).

Williamson, C.E.; Zagarese, H.E. 1994. Impacts of UV-B on pelagic freshwater ecosystems. Wiley and Sons, NY.

Wilson, L.; Vallee, M.; Tarasick,D.; Kerr, J.; Wardle, S. 1992. Operational forecasting of daily total ozone and ultraviolet-B radiation levels for Canada. Atmospheric Research Service, Environment Canada. Research Report No. 92-004.

Winstanley, D.; Lackey, R.T.; Warnick, W.L.; Malanchuk, J. 1998. Acid rain: science and policy making. Environmental Science and Policy 1: 51-57.

Yan, N.D.; Keller, W.; Scully, N.M.; Lean, D.R.; Dillion, P. 1996. Increased UV-B penetration in a lake owing to drought-induced acidification. Nature 381: 141-143.