Atmospheric Deposition and Its Effects in the Intermountain West

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The Intermountain region of the western United States includes vast arid and semi-arid lands that would likely benefit from acid rain or any other type of rain they could get. But it also includes high-elevation alpine and subalpine ecosystems that are among the most sensitive in the world to harmful effects of atmospheric deposition.

These sensitive areas include some of the crown jewels of the National Parks and National Forest Wilderness areas. Many are Class 1 areas protected by the Clean Air Act Amendments from any degradation of air-quality-related values, including degradation that might be caused by atmospheric deposition. This discussion focuses on these sensitive areas by examining spatial and temporal trends in atmospheric deposition, ecosystem sensitivity and response to deposition, and concerns for protection of these ecosystems in the future.

In the Intermountain region, elevational gradients determine regional patterns in precipitation, with higher elevations receiving greater precipitation. Variability in precipitation amounts is generally greater than variability in concentrations of pollutants, so deposition is usually greater at higher elevations as well. Mountain ecosystems are sensitive to atmospheric deposition because they often have bedrock that is resistant to weathering, which results in poorly buffered soils, ground water, and surface water. Cold temperatures and a seasonal snowpack that persists for 6-10 months limit the growing season and the ability of ecosystems to assimilate nitrogen in atmospheric deposition. Much of the annual load of pollutants in atmospheric deposition is delivered to the ecosystem during a few weeks of spring snowmelt. Thus, in the Intermountain region high-elevation areas that receive the greatest amounts of atmospheric deposition also contain ecosystems that are most vulnerable to impacts from that deposition.

Spatial and Temporal Trends in Atmospheric Deposition of Sulfur and Nitrogen

Total loadings (deposition) of pollutants are important for assessing ecosystem effects, however, spatial and temporal trends in deposition are confounded by natural variability in precipitation amounts. Trends are discussed here in terms of concentrations in order to minimize the effects of climate and focus on variability caused by anthropogenic emissions. In order to better capture the spatial variability in amounts and sources of atmospheric deposition to the Rocky Mountains, concentrations and isotopic signatures of pollutants are measured in the seasonal snowpack at maximum accumulation during the spring [Turk et al. 2001; Mast et al. 2001; Campbell et al. 2002].

Sulfate concentrations in the snowpack generally increase from north to south along the Continental Divide, and both concentrations and isotopic signatures of sulfate are related to anthropogenic sources of sulfur dioxide emissions [Turk et al. 2001; Mast et al. 2001]. Spatial trends for hydrogen ion concentration (acidity) are similar to those for sulfate [Turk et al. 2001]. Greatest acidity and sulfate concentrations in the snowpack have been found in the Park Range in northwestern Colorado (Figure 1), an area downwind of coal-fired power plants that have recently begun installing emissions controls as a result of a legal settlement regarding visibility impairment to Class 1 Wilderness Areas [Turk and Campbell 1997]. Elevated concentrations of sulfate are also found in other areas near emissions sources such as northcentral Colorado, southeastern Wyoming, and northern New Mexico. Concentrations of sulfate in wet deposition were either unchanged or decreasing from 1981–1998 at all sites in the Intermountain region, which is similar to trends

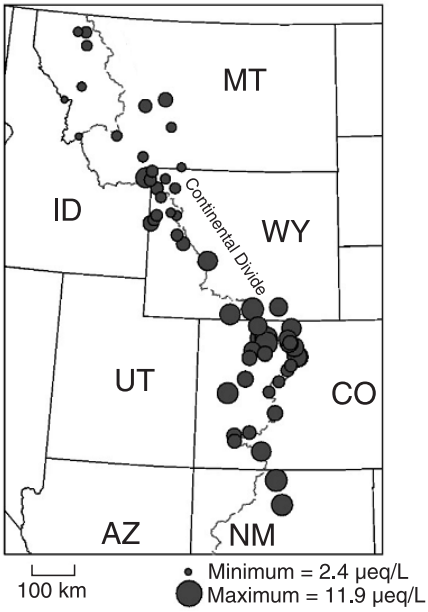

Figure 1. Average sulfate concentrations in snowpack for 1993-2000 [after Turk et al. 2001].

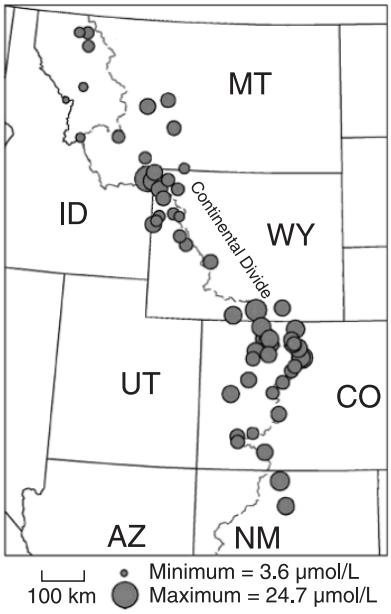

Figure 2. Average dissolved inorganic nitrogen concentrations in snowpack for 1993 – 2000 [after Turk et al. 2001. Ecosystem Response to Deposition of Acids and Nitrogen

resulting from decreased sulfur dioxide emissions in other parts of the country [Nilles and Conley 2001].

Spatial trends in snowpack concentrations of dissolved inorganic nitrogen (DIN) are similar to those for sulfate and acidity, except that the local areas of high deposition in northern Colorado are more widespread than they are for sulfate, and nitrogen deposition in northwestern Wyoming also is high (Figure 2) [Turk et al. 2001]. Ammonia makes up about one-third of the total nitrogen deposition at many sites, and is important for its contribution to fertilization of ecosystems as well as its potential acidifying effect as it is assimilated or nitrified in the ecosystem. In contrast to sulfate, concentrations of nitrate and ammonia were either level or increasing from 1981–1998 at all sites in the Intermountain region [Nilles and Conley 2001].

The snowpack concentration data can be combined with wet deposition measurements collected at the National Atmospheric Deposition Program / National Trends Network (NADP/NTN) sites [N*ational Atmospheric Deposition Program / National Trends Network*, 2001] and high-resolution precipitation maps [Daly et al. 1994] to produce high-resolution maps of deposition that better incorporate precipitation amount gradients than maps using the NADP/NTN data alone [Nanus et al. 2000]. These deposition maps illustrate regional trends in atmospheric deposition caused by precipitation amount and regional emissions, as well as highlight areas that are affected by local sources of pollutants.

The Intermountain region is fortunate to have deposition rates of acidity, sulfate, and nitrogen that are moderate compared to some parts of the world. Chronic acidification from atmospheric deposition has not been documented in any lakes or streams that do not have acid rock drainage, in the western United States. Episodic acidification is more difficult to evaluate because few sites have sufficient data, but its effects are likely found in only the most sensitive high-elevation lakes and streams. A recent study in the Park Range, however, indicates that many ephemeral ponds are much more sensitive to acidification than nearby

lakes, with acid-neutralizing capacities reaching less than 20 ueq L-1 during parts of the summer [Muths et al., 2002].

Nitrogen deposition contributes to acidification of ecosystems in advanced stages of nitrogen saturation, but, in earlier stages, there may be other ecosystem effects that are more subtle. Elevated amounts of nitrogen in soils may disrupt soil nutrient cycling processes before inorganic nitrogen appears in surface waters. Advanced symptoms of watershed nitrogen saturation have resulted from atmospheric nitrogen deposition levels of 3-5 kg ha-1 y-1 in high-elevation ecosystems of the Colorado Front Range [Williams et al. 1996]. Front Range ecosystems have greater nitrogen content in soil and vegetation and higher potential net mineralization rates in soil compared to other areas in Colorado with lower nitrogen deposition rates [Baron et al. 2000]. Even in areas with little vegetation and soil, isotopic signatures of nitrate in surface and ground water indicate that most of the atmospherically-deposited nitrogen has been biologically cycled [Campbell et al. 2002], underscoring the importance of soil microbial processes in all landscapes. Export of nitrate from the terrestrial ecosystem results in higher concentrations of nitrate in lakes [Baron et al. 2000; Clow et al. 2002], and changes in community composition and biovolume of diatoms in lakes [Baron et al. 2000; Wolfe et al. 2001].

Although there has been substantial research on ecosystem response to atmospheric nitrogen deposition in the Front Range of Colorado and nearby areas, little or no data are available regarding the status of many high-elevation ecosystems in other areas of the Rocky Mountains. A survey of 370 lakes in and near National Forest Class 1 Wilderness Areas provides a snapshot of other high-elevation areas that are potentially sensitive to atmospheric nitrogen deposition (Figure 3). Most of these wilderness areas have nitrogen deposition rates of 2 kg ha-1 or less (about one-half of that found in the Front Range). Yet there were lakes in almost every area that had measurable nitrate concentrations during late summer, when ecosystem nutrient demand causes nitrate concentrations to reach their annual minimum. This leakage of nitrogen from the ecosystem indicates watershed

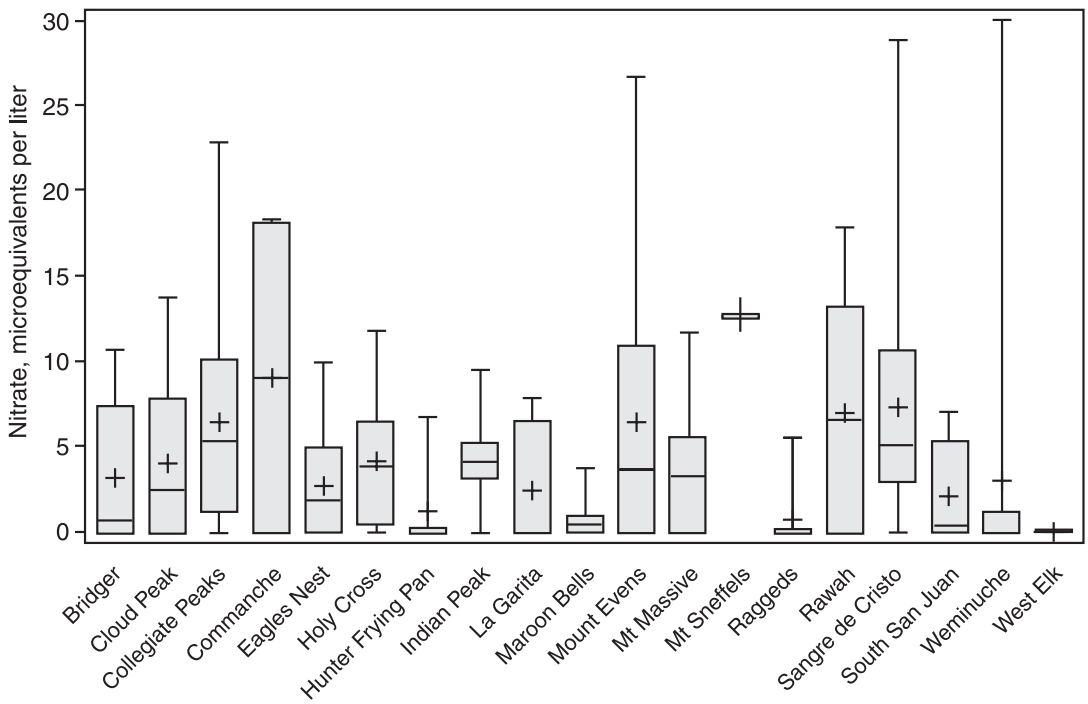

Figure 3. Nitrate concentrations in National Forest Lakes of Wyoming and Colorado, by Wilderness Area. Total number of lakes is 331.

nitrogen saturation at levels of nitrogen deposition that were not previously thought to cause ecosystem effects. Previous studies based on the Front Range data suggested a critical threshold of 3-6 kg ha-1 before advanced effects of nitrogen saturation such as nitrate leakage would be seen [Williams and Tonnessen 2000; Burns 2002]. These results indicate a need for better understanding of ecosystem sensitivity to nitrogen deposition, and re-examination of critical thresholds of nitrogen in atmospheric deposition to undisturbed high-elevation ecosystems. The role of organic nitrogen in nitrogen cycling and transport also needs to be examined in ecosystems with both moderate and high levels of nitrogen deposition [Williams et al. 2001].

Trends in Emissions

The primary source of sulfate and related acidity in atmospheric deposition of the Intermountain region is coal combustion for electric power generation. Decreased emissions of sulfur dioxide from some existing plants is expected as improved emissions controls are installed. However, there are also new coal-fired power plants planned or under construction, and development of new sources of energy such as oil shale could also increase regional emissions.

Emissions of nitrogen compounds come from a wider range of sources. Fossil-fuel combustion in motor vehicles contributes a large amount of nitrogen oxides, and increases in both population and per-capita vehicle miles are expected to continue. The extent to which this trend could be offset by improvements in vehicle emissions controls is uncertain. Electric power generation from combustion of both coal and natural gas also contributes substantial emissions of nitrogen oxides. As with sulfur dioxide emissions, some power plant emissions will be reduced by installation of emissions controls, but new coal and natural gas fired power plants are planned or under construction. In addition, further development and production of fossil fuels reserves such as natural gas, coal-bed methane, and oil shale will also add to emissions of nitrogen oxides. Because many of these reserves are located near sensitive high-elevation ecosystems in the region, these emissions may have acute local effects as well as contribute to regional emissions.

Emissions of ammonia come primarily from agricultural sources such as animal waste and volatilization of fertilizer applied to crops, but may also come from motor vehicles and industrial sources. Fertilizer use has increased rapidly during the last 50 years in the Intermountain region as it has worldwide [Baron et al. 2000], and livestock production has increased in some areas such as northeastern Colorado where large confined animal feeding operations exist.

Toxic Pollutants in Atmospheric Deposition

The abundance and effects of toxic pollutants in atmospheric deposition in the Intermountain region are poorly understood. The only high-elevation site where mercury deposition has been monitored in the Rocky Mountains is Buffalo Pass, in the Park Range of Colorado [National Atmospheric Deposition Network Mercury Deposition Network, http://nadp.sws.uiuc.edu/mdn/]. Mercury deposition at Buffalo Pass averaged 9 µg m-2y-1 in 2000, which is comparable to mercury deposition at sites in the Midwestern and Northeastern United States, where fish consumption advisories are common. Significant atmospheric mercury deposition to Rocky Mountain National Park also is indicated from sediment cores collected at Mills Lake [Krabbenhoft et al. 2002].

Persistent organochlorine compounds and current-use pesticides in atmospheric deposition are another concern. Concentrations of total DDT (DDT + DDE + DDD) as high as 14 µg kg-1 have been measured in lake sediments in Rocky Mountain National Park [P. Van Metre, U. S. Geological Survey, written communication]. In the mountains of western Canada, deposition of organochlorine compounds was shown to increase with altitude, and concentrations of more volatile compounds were enhanced by cold-condensation [Blais et al.1998].

Conclusions

Chronic acidification of surface waters from atmospheric deposition is not a widespread problem in the Intermountain region. Episodic acidification is a concern in some high-elevation headwaters and in some ephemeral ponds. Recent trends of decreasing sulfate in deposition suggest that acidification from sulfur compounds is not getting worse; however, it is unclear whether these trends will persist in the future, and they may be offset by increasing trends in deposition of nitrogen compounds.

Fertilization effects of nitrogen deposition on high-elevation ecosystems are currently the greatest concern related to atmospheric deposition. Both terrestrial and aquatic effects have been demonstrated at levels of nitrogen deposition that are now occurring in some parts of the region. Recent trends and future projections suggest that nitrogen deposition is likely to continue increasing, which would intensify ecosystem effects and expand their areal extent.

In order to protect sensitive ecosystems while managing growth and energy development in the Intermountain region, better understanding of source-receptor relations for specific pollutants and ecosystem responses to changes in atmospheric deposition and climate is needed. More monitoring and research is also needed in areas that currently are showing ecosystem responses to moderate levels of atmospheric nitrogen deposition. Finally, there is a need for monitoring and research on the distribution and effects of atmospherically-deposited toxic compounds such as mercury and pesticides.

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