# Winter Deposition of Nitrogen and Sulfur in the Eastern Columbia River Gorge National Scenic Area

Final Report to the USDA Forest Service, Region 6 Air Resources Program

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## Executive Summary

As a preliminary evaluation of the potential impacts of air pollution on natural and cultural resources in the eastern Columbia River Gorge (CRG), nitrogen (N) and sulfur (S) deposition in fog, bulk deposition and throughfall and the level of acidity of fog and precipitation were monitored during the winter wet season (2003-2004). Atmospheric deposition samples were collected at eleven sites along the CRG, with a focus on the National Scenic Area in the eastern end of the gorge. Nitrogen deposition inputs in throughfall were surprisingly high with N deposition fluxes ranging from 11.5 to 25.4 kg $ha^{-1}$. Ammonium deposition in throughfall was higher in the more easterly sites, presumably because of agricultural emissions of ammonia and possibly industrial emissions. As expected, ionic concentrations of N and S were many-fold higher in fog than in bulk precipitation and the pH of fog was generally lower than the pH of precipitation. The pH of fog and bulk deposition varied temporally, but pH values were commonly between 4.0 and 4.5 and lower than 4.0 in some instances. The levels of atmospheric deposition, and particularly that of N, are at levels shown to have ecological impacts in western ecosystems as a result of N enrichment. Impacts of N deposition on sensitive lichen communities in the gorge has already been demonstrated. Further studies are needed to more fully ascertain the impacts of acidic deposition and N enrichment on cultural and natural resources within the eastern CRG.

## Introduction

The Columbia River Gorge National Scenic Area, located along a portion of the Oregon/Washington border, is an area highly valued for its scenic, cultural, and natural resources. Unfortunately the Columbia River Gorge (CRG) has also become a conduit of air pollution transport from emissions sources located within the gorge and to the west and east of the gorge. This study was initiated to determine the level of nitrogen (N), sulfur (S) and acidic deposition occurring in precipitation, fog or cloudwater. The combined deposition of N and S in wet and dry forms was also estimated from throughfall measurements. Throughfall is the flux measurement of N and S washed from tree canopies during precipitation and fog events.

In the Columbia Basin in winter (November to early March) air stagnation episodes are a relatively frequent event. During these events, which can last for days to weeks, air pollution

emitted in the basin is trapped by the geographic barriers around the basin and capped by a temperature inversion which settles over the region preventing vertical mixing or transport of the trapped air mass. The CRG is the primary outlet for this polluted air mass. The cold dense and very humid air settles into the lowest areas – particularly the river bottom and in the eastern end of the gorge. This air mass slowly drains westward and out of the basin as it moves through the Gorge. The cold air mass drainage flow is often accompanied by low clouds and fog which entrain the trapped air pollutants.

Pollution sources in the basin, concentrated mostly along the rivers, include a number of recently constructed power plants, mostly natural gas, but including the Boardman Coal Fired Power Plant, located about a hundred km east of the Scenic Area which is the largest point source in the Columbia Basin. This source emitted 13119 tons/year of $SO_2$ and 10080 tons of NOx in 2003 from EPA compiled inventories. Notably, the area immediately adjacent to Boardman includes a very large feed lot, a point source of ammonia emissions. Several proposed new plants have permits and are under construction or are waiting for energy market conditions to improve before construction is commenced. Several are in the permitting stage. With the large number of existing and proposed facilities the basin has become an energy farm. Additionally there are four aluminum smelters – two in the gorge at The Dalles and Goldendale, a third near Wenatchee, and one in Spokane. However, these facilities are currently shut down or operating at low capacity because of poor market conditions – the smelters were not operating at the time of this study. There is also a pulp and paper mill and a fertilizer plant at Wallula, several food processing plants with boilers at Boardman, and extensive agricultural operations with large acreages of grain crops. A number of urban areas are also found within the river gorge and in the surrounding areas, including Pendleton, Hermiston, the Tri Cities, Hood River, The Dalles, Yakima, Ellensburg, Wenatchee, Spokane, Walla Walla, and smaller communities. Each of these has the expected suite of urban emissions mostly dominated by transportation. The gorge also has two railroad tracks with trains approximately every 20 minutes, two major highways with car and truck volume, and on-river barge traffic. In the cumulative sense all of these sources contribute to the basin and gorge air quality problem -- generally in proportion to their size, distance, and local meteorological conditions.

The polluted air mass that drains thru the CRG in winter is believed to be responsible for an air pollution signature seen in the lichen tissue samples and lichen species community shifts (Geiser and Neitlich, 2003). Lichens are an excellent bioindicator for air pollution effects. In this case lichen species sensitive to high S concentrations are largely absent even though these species are endemic to the area. Some weedy lichen species known to thrive in N rich polluted environments are abundant (Fenn et al., 2003). Lichen tissues absorb pollutants. Tissue samples from pollution-tolerant species have been analyzed for N and S concentrations. The N and S concentrations of the lichen tissue collected in the CRG are relatively high compared to other areas in the Pacific Northwest. This information indicates high N and S deposition rates in the CRG.

The potential acidity of atmospheric deposition in the CRG has raised concerns that protected cultural resources, particularly Indian rock art, are being harmed and over time will deteriorate from winter immersion in this polluted air mass. The data on changes in the chemistry and community composition of lichens indicates other adverse ecosystem effects are occurring as a result of atmospheric deposition. The purpose of this study was to quantify N and S deposition in fog, bulk precipitation and throughfall and to measure the acidity of fog and bulk precipitation at sites located across the CRG as an indicator of the potential for ecological and environmental impacts of current levels of atmospheric deposition.

## Methods

Atmospheric deposition monitoring was carried out at eleven sites across the CRG (Fig. 1 and Table 1). Three types of samples were collected. Bulk precipitation and fogwater were collected in open areas, and throughfall was collected under ponderosa pine (*Pinus ponderosa* Laws.) canopies. Bulk deposition was collected at all eleven sites, and throughfall was collected at all sites except Mt. Zion (MZ) and Wishram (WI) where there were no pine trees. Fog samples were collected at seven sites. The sample collectors were installed in the monitoring sites during the last week of October 2003 and continued to collect samples until March 9, 2004, for a total collection period of 19 weeks, or nearly 4.5 months. Three replicate bulk deposition collectors were installed at each site. Ten throughfall collectors were installed per site, distributed under 5-7 trees, except at Celilo where due to access limitations, four throughfall collectors were placed under a single large pine tree.

Table 1. Sites within the Columbia River Gorge at which atmospheric deposition samples were collected.

| Site Name | Site abbreviation and type of samples collected[§] | Elevation (m) | Coordinates |
|---|---|---|---|
| Mt. Zion | MZ (bp, f) | 225 | N 45° 34' 9.84"<br>W 122° 12' 41.04" |
| Twin Tunnels High | TTH (bp, tf) | 164 | N 45° 41' 32.77"<br>W 121° 27' 01.97" |
| Twin Tunnels Low | TTL (bp, tf) | 115 | N 45° 41' 25.94"<br>W 121° 26' 48.29" |
| Catherine Creek High | CCH (bp, tf) | 385 | N 45° 43' 20.66"<br>W 121° 22' 58.98" |
| Catherine Creek Low | CCL (bp, tf) | 125 | N 45° 42' 45.28"<br>W 121° 21' 57.34 |
| Sevenmile Hill | 7MH (bp, f, tf) | 520 | N 45° 38' 13.20"<br>W 121° 17' 55.72" |
| Klickitat | KLICK (bp, tf) | 207 | N 45° 43' 23.76"<br>W 121° 15' 32.62" |
| Horse Thief State Park | HTSP (bp, f, tf, wd) | 33 | N 45° 38' 41.42"<br>W 121° 06' 26.87" |
| Wishram | WI (bp, f) | 232 | N 45° 39' 56.98"<br>W 121° 00' 2.59" |
| Celilo | Celilo (bp, f, tf) | 19 | N 45° 39' 03.89"<br>W 120° 57' 34.73" |
| Maryhill | MH (bp, f, tf) | 216 | N 45° 40' 37.36"<br>W 120° 51' 59.19" |

[§]Types of samples are as follows: bulk precipitation (bp), fog (f), throughfall (tf), or wet deposition (wd). Note that fog collectors were installed at Klickitat, but no data are presented because of infrequent fog events, very low fog sample volumes and vandalism of the collectors.

The most westerly site was MZ, which is a National Atmospheric Deposition Program (NADP) monitoring site, that is located at the Portland end of the Gorge. The other ten sites are to the east within the CRG National Scenic Area (Fig. 1). Precipitation decreases dramatically from west to east across the CRG. From Bonneville Dam, near MZ to the west of the Scenic Area to The Dalles in the eastern end of the gorge within the National Scenic Area, annual precipitation in the 2003/2004 water year decreased from 176 cm to 39 cm (Table 2).

Bulk precipitation samples were collected with a standard rain gauge funnel (10 cm i.d.) connected to a polyethylene storage bottle. Throughfall samples were collected under ponderosa pine trees with collectors using the same funnels described for the bulk precipitation samplers. Deposition of N and S in throughfall was collected using ion exchange resin (IER) throughfall collectors which are composed of a funnel collector opening that directs throughfall (precipitation collected below tree canopies) solutions to percolate through an IER column. Details of these IER collectors are described in Fenn and Poth (2004). These collectors are designed so that liquid samples are not collected. Instead, ions in the throughfall solutions are captured by the IER within the columns. At the end of the monitoring period, the resin columns were extracted with 1*N* potassium iodide as described by Simkin et al. (2004). Nitrate and sulfate in the extracts were analyzed by high performance ion chromatography (Dionex, Model DX600; Sunnyvale, CA) and ammonium was analyzed with a TRAACS 800 Autoanalyzer (Tarrytown, NY). At the Twin Tunnels (TTL, TTH) and Catherine Creek (CCL, CCH) sites, bulk deposition was also collected with IER collectors as opposed to weekly collections of liquid samples. Throughfall measurements provide a measure of deposition fluxes under plant canopies. Plant canopies function as effective fog and dry deposition collectors, resulting in elevated ionic deposition to the soil under the canopy. Thus, the areas under plant canopies receive the brunt of concentrated pollutant deposition in fog or cloudwater and washoff of accumulated dry deposition.

Fog samples were obtained with passive fog line collectors that collect fog or cloudwater, using a design slightly modified from that described in Fenn et al. (2000). The fog collecting surface was composed of 168 teflon strings, 30 cm in length, arranged in two concentric circles, 8.0 and 8.2 cm in diameter. The teflon strings were 0.4 mm in diameter. The liquid collected by the strings during fog events drained into a funnel base and was collected in a polyethylene bottle. A plastic trash can lid (0.5 m diameter) was mounted above the fog collectors to prevent the collection of rain from above. However, it should be noted that the passive fog collectors were not designed to exclude the collection of wind-blown precipitation. Thus, some of the fog samples are likely to include precipitation in some instances. However, the much higher ionic concentrations of the samples collected by the fog samplers compared to the bulk deposition samples demonstrate that a large proportion of the sample volumes collected was fog water. Bulk precipitation and fog samples were collected for field pH measurements and laboratory analysis for N and S on a weekly basis. Samples were shipped overnight to the Forest Fire Laboratory in Riverside, CA for analysis. Nitrate and ammonium in bulk deposition and fog samples were measured with the TRAACS 800 Autoanalyzer and sulfate was determined with a Dionex ion chromatograph. The pH of fog and bulk deposition samples was determined with a portable pH meter in the field. Sample pH was also measured in the lab after shipping the samples to

Riverside, CA but lab pH values were consistently higher than field pH values. The field pH values are considered to be more reflective of sample pH and thus the lab pH values are not reported.

At Horsethief State Park (HTSP) an NADP wet deposition collector was also installed for comparison of wet deposition fluxes to bulk deposition fluxes measured with the bulk precipitation collectors. The latter includes a small component of dry and fog deposition that collects on the collector funnels in between precipitation events because the funnel is constantly exposed to the atmosphere.

## Results

Throughfall:

Deposition of N and S in throughfall under pine trees was highest at Seven Mile Hill (7MH) with throughfall deposition of 25.4 kg N/ha and 6.5 kg S/ha. Deposition of $NH_4^+$ and $NO_3^-$ were of similar magnitude at 7MH. At sites to the west of 7MH $NO_3^-$ deposition in throughfall was generally greater than $NH_4^+$ deposition. At sites east of 7MH, $NH_4^+$ deposition in throughfall was greater than $NO_3^-$ deposition (Fig. 2).

Deposition of $NH_4^+$ in throughfall was greater in the sites located to the east of 7MH (average of 8.01 kg N/ha) compared to sites west of 7MH (average of 2.76 kg N/ha; Table 3). The east:west ratios of throughfall deposition inputs were 1.16, 2.90 and 1.36 for $NO_3^-$, $NH_4^+$, and $SO_4^{2-}$.

Nitrate deposition in throughfall was higher than $SO_4^{2-}$ deposition at all nine sites. Only at CCH was $SO_4^{2-}$ deposition similar to $NO_3^-$ deposition (Fig. 2). Average values for $NO_3^-$ deposition were generally higher than $NH_4^+$ deposition except at two of the three most easterly sites (HTSP and Celilo). These are also the two sites with the lowest elevation. Deposition of $NH_4^+$ and $SO_4^{2-}$ in throughfall are highly similar at all sites west of 7MH, but at 7MH and all the sites east of 7MH $NH_4^+$ deposition was 2-3 times higher than $SO_4^{2-}$ deposition (Fig. 2).

Bulk Deposition:

Spatial patterns of bulk deposition differed from those for throughfall. Bulk deposition is based primarily on wet deposition with minimal inputs from dry deposition and fog. In contrast to the throughfall data, bulk deposition of $NO_3^-$, $NH_4^+$, and $SO_4^{2-}$ were all higher on average at the sites to the west of 7MH compared to the eastern sites (Fig. 2). While N and S deposition in throughfall was by far the highest at 7MH, bulk deposition of the three ions at 7MH were similar to the average bulk deposition fluxes at the western sites and higher than the eastern sites (Fig. 2). Another contrast with the throughfall data is that for throughfall, $NH_4^+$ deposition tended to be higher than the other ions in the eastern sites, while in bulk deposition $NO_3^-$ was consistently higher than $NH_4^+$ or $SO_4^{2-}$ deposition in the eastern sites, suggesting that $NH_3$ was predominantly deposited in fog and possibly as dry deposition.

Fog Deposition:

Although the passive fog collectors were not designed to prevent the collection of wind-blown precipitation from the side, the fog collectors seem to have sampled mostly fog, as evidenced by the low volumes and the much greater chemical concentrations of the fog collector samples compared to the bulk deposition samples (Fig. 3). However, at MZ and 7MH the high volumes in the fog collectors on many dates (and low ionic concentrations in fog at MZ) suggest that at

these two sites wind blown precipitation was collected in the fog collectors along with fog samples. At Klickitat (KLICK) and Celilo liquid samples were only collected in the fog samplers on one sampling date. This result, along with the low fog volumes relative to precipitation volumes and high ionic concentrations in the fog collector samples, suggest that contamination of fog samples by rain or snow was probably minor in sites other than MZ and 7MH. Ionic concentrations were very high in the two samples from KLICK and Celilo, but the volume collected at KLICK was very low (< 10 ml).

Deposition Acidity:

The pH of fog and precipitation varied temporally at all the study sites. On a few occasions pH values were greater than or equal to 5.7, particularly near the beginning of the study in November or early December 2003. The most acidic samples were collected at WI in January 2004. However, the fog samples at 7MH were the most consistently acidic, with fog pH values ranging from 3.8 to 5.0 from early December 2003 through March 2004. On 9 of 12 sampling dates during this period, fog pH at 7MH was less than 4.5. Bulk precipitation at 7MH did not go below pH 4.5. Precipitation or fog pH values of 4.5 or lower occurred at KLICK (4 dates), HTSP (2 dates), Celilo (3 dates), WI (3 dates, all as fog), and Maryhill (MH; 2 dates, as fog and bulk precipitation). At MZ the pH of the bulk fog and bulk deposition samples were usually between 5.0 and 6.0 except for five dates when the pH of fog samples was between 4.5 and 5.0 and once when fog pH was 6.4-6.6. A similar temporal trend of lower pH values during the latter part of the study was also observed at KLICK, HTSP, Celilo, WI and MH.

The pH of bulk precipitation at Klickitat ranged from 4.1-5.4 compared to a range of 4.6 to 5.8 at HTSP. Fog volumes were very low at HTSP so pH was only measured on two dates. In both instances, fog pH was slightly higher than bulk precipitation pH (Fig. 4). The pH of bulk precipitation at Celilo ranged from 4.2-6.3. At WI the pH of bulk precipitation ranged from 4.7-6.4 and the pH of fog ranged from 3.7-6.7. On three sampling dates in December and January fog pH values at WI were between 3.7 and 4.5 (Fig. 4). At MH bulk precipitation pH was 4.7-6.4. On the three dates when fog samples were collected at MH, fog pH varied widely with average values of 6.7, 4.4 and 5.6. Fog pH at MH was generally higher than the pH of bulk precipitation (Fig. 4).

At MZ, 7MH and WI fog samples were usually more acidic than bulk precipitation, although in some cases pH was similar or less acidic in fog. On the 1-3 dates when field pH was measured in fog at HTSP, Celilo and MH fog was less acidic than bulk precipitation (Fig. 4).

## Discussion

This was a short term study, covering only the major wet season from late October 2003 to early March 2004, a period of slightly over four months. The first storm of the wet season occurred before sampling began in late October 2003. In the CRG National Scenic Area 4-5% of the annual precipitation occurred in October, before we began sampling. Thus, we did not sample the initial rain events of the new water year. These first rain events often entail the highest deposition fluxes in throughfall as pollutants that accumulate on plant canopies during the dry summer are washed off. For example, at the Hood River and The Dalles meteorological stations, respectively, only 1.42 and 0.23 cm of precipitation were recorded from June through September 2003. This long dry period preceding the October rain events, suggests that these first rain events that were not sampled may have contained higher levels of accumulated N and S compounds

than in subsequent rain events with much shorter antecedent dry periods. Based on the high $NH_4^+$ deposition fluxes in this study, dry deposition in the summer would presumably result largely from $NH_3$ emissions from agriculture and other sources. In summary, the deposition fluxes in throughfall would likely have been significantly higher if throughfall sampling had begun in early October. This conclusion assumes that dry deposition is an important atmospheric deposition component in the CRG.

The sampling period of this study included the major wet season, so it is expected that we measured the major inputs from fog and wet deposition. Throughfall deposition inputs reported in this study are considered to be lower than annual throughfall fluxes since we only sampled for 4.5 months. For the 2004 water year (Oct 2003 to September 2004) 69-74% of the annual precipitation occurred during the monitoring period of this study (Table 3), based on precipitation data from Hood River and The Dalles (http://ippc2.orst.edu/cgi-bin/ddmodel.pl). Although, the throughfall fluxes were relatively high in the CRG during this 4.5 month study, annual inputs to forested areas from fog, wet and dry deposition of N and S are expected to be much higher.

Levels of Atmospheric Inputs in the CRG:

Atmospheric deposition inputs of N in throughfall were high under ponderosa pine trees in this study. Both oxidized and reduced forms of N were important contributors to atmospheric N deposition inputs based on throughfall $NO_3^-$ and $NH_4^+$ flux data. Nitrate was generally the more important ion at sites west of 7MH, while $NH_4^+$ increased in relative importance at 7MH and sites further east. Elevated $NO_3^-$ deposition is typical of areas exposed to emissions from fossil fuels, generally from transportation and industrial sources. Elevated $NH_4^+$ deposition generally reflects agricultural sources, such as confined animal feeding operations, although emissions from the transportation sector, sewage and industrial sources can also contribute.

Throughfall fluxes reported in this study represent deposition inputs under ponderosa pine trees. Deposition to open or canopy-free areas will be lower because tree canopies serve as collection surfaces for deposition in fog and dry deposition. Thus, deposition over the larger landscape will depend largely on the extent of canopy cover. Nitrogen deposition inputs in throughfall at 7MH (25.4 kg N/ha) were the highest reported in this study. It is widely reported in the literature that at these levels of deposition significant impacts on nutrient cycling and on plant, soil and aquatic chemistry can be expected (Fenn et al., 2003). Commonly observed effects include increased site N status observed as reduced C:N ratio of the mineral soil and organic layer, and increased foliar N, soil acidification, N cycling and N mobilization. Nitrogen is mobilized and exported from the site as leached nitrate and gaseous emissions of N from soil. The key process mediating these effects is increased nitrification in soil. On the watershed level, elevated $NO_3^-$ concentrations in streamwater are commonly observed.

Spatial Trends in Deposition:

Inputs of $NO_3^-$, $NH_4^+$ and SO4 in bulk deposition were higher in the sites west of 7MH, presumably because of higher precipitation amounts in the western end of the CRG. Bulk deposition is composed of wet deposition plus a minor component of dry deposition that occurs to the funnel collectors between precipitation events. Thus, it is to be expected that in sites further west with higher precipitation will show higher bulk deposition levels, even though bulk deposition inputs were low at all the sites compared to throughfall inputs. These patterns

demonstrate the greater importance of atmospheric inputs of N and S in fog and as dry deposition to forested areas compared to deposition in precipitation.

Several factors lead to greater atmospheric deposition in fog or in dry form compared to deposition in rain or snowfall. First of all, ionic concentrations in rain or snow are typically very low, while ionic concentrations are many-fold higher in fogwater or cloudwater. Dry deposition of pollutants to forest canopies or to other surfaces is a major deposition pathway because this is a chronic and continuous deposition process during precipitation-free periods. Dry-deposited N and S compounds accumulate on forest canopies until a precipitation event, at which time a flush of compounds are washed from the canopy as throughfall deposition to the forest floor. Thus, throughfall deposition provides an estimate of dry and fog deposition.

Higher concentrations of $NH_4^+$ deposition in throughfall at 7MH at sites east of there suggests that higher levels of $NH_4^+$ in fog and/or dry deposition occurred in the more easterly sites compared to the more westerly sites of the Scenic Area during the monitoring period. Nitrogen concentrations in tissue of the lichen *Xanthoparmelia cumberlandia* were also higher in the eastern end of the Gorge compared to western sites (Linda Geiser, personal communication). The most likely ammonia emissions sources for the CRG Scenic Area include the large feedlot surrounding the Boardman power plant, crop fertilization, a fertilizer plant along the river in the Tri Cities area, and power plant emissions.

Nitrogen versus Sulfur Deposition:

In throughfall in the sites west of 7MH, nitrate concentrations were higher than ammonium or sulfate concentrations and ammonium concentrations tended to be slightly greater than sulfate concentrations. This reflects the emissions profile of the urban source area (greater Portland) that is the major influence on the western end of the gorge. High levels of NOx are expected because of emissions from the largely urban transportation sector. At 7MH and in sites east of 7MH, the throughfall deposition pattern was generally $NH_4^+ > NO_3^- > SO_4^{2-}$, which is reflective of the greater agricultural emissions near the eastern end of the CRG.

Acidic Deposition Effects on Cultural and Natural Resources:

Precipitation in equilibrium with $CO_2$ has a pH of 5.65, slightly acidic because of the weak carbonic acid formed by the dissolution of $CO_2$ in water. A pH value of precipitation of 5.65 can can thus be used as a benchmark in evaluating the extent to which air pollutants may be increasing the acidity of precipitation or fogwater.

The finding of fog or bulk precipitation samples with a pH of 4.5 or lower on more than one sampling date at all six of the monitoring sites east of MZ demonstrates that acidic deposition is occurring throughout the CRG National Scenic Area. The pH of fog or bulk precipitation samples were never below 4.5 at MZ. More extremely acidic events, here defined as pH less than 4.0 occurred on three sampling dates at 7MH and once at WI and MH. However, more sampling dates with unusually low pH values may have been found if the fog collectors had the capacity to reliably exclude wind-blown precipitation and collect only fogwater.

The detrimental effects of acidic deposition on rock buildings and stone monuments of certain rock types (e.g., marble) is well known. However, the rock art in the CRG National Scenic Area is largely on basalt or other rock types of volcanic origin. The level of acidity in the precipitation

and fog samples collected in this study suggests that the potential for increased risk of deterioration of cultural resources such as rock paintings should be investigated. Damage to stone from acid deposition is a complex process that depends on many factors, and we cannot assess or predict the level of damage to rock art in the Gorge from the available information. Previous research has found minimal stone degradation in the arid southwestern U.S. However, studies have found that dry deposition of S and N compounds is the main source of stone deterioration. Nonetheless in areas where stone materials remain wet for long periods of time, wet deposition can be a significant or primary cause of damage (Charola, 2001; NAPAP, 1998). Futhermore, lichen growth can affect the integrity of petroglyphs (Dr. Ron Dorn, Arizona State University, personal communication). It is well documented that atmospheric deposition has caused changes in lichen communities and the elemental composition of lichens in the CRG National Scenic Area. This raises questions in regard to indirect effects of N deposition on rock art by way of changes in lichen communites colonizing the rock art.

Possible Ecological Effects of Nitrogen and Sulfur Deposition:

Two main types of ecological effects are of concern from the deposition levels indicated by this study. Increased soil acidification is one response to chronic N and S deposition. Eutrophication or N enrichment effects is the other major category of ecosystem effects, and is in fact the most common response in Western forests (Fenn et al., 2003). Air pollution impacts on lichen communities in the CRG, attributed to N deposition are well documented. Lichen communities in many areas of the CRG have shifted to a higher proportion of nitrophilous species and the N content of lichen tissue is elevated (Fenn et al., 2003). Recent studies show that the N content of the lichen *Xanthoparmelia cumberlandia* is significantly higher in the eastern end of the Gorge compared to the western end. These findings agree with the throughfall data in this study. Throughfall is a good indicator of total N and S deposition because it includes deposition from dry deposition, fog deposition and wet deposition. The throughfall data also suggest that over half of the N deposition is in reduced form, suggesting an agricultural or industrial source in the eastern end of the gorge.

Lichens are sensitive indicators of N deposition effects to terrestrial ecosytems, andt the lichen studies in the CRG clearly show that ecological effects from air pollution are occurring. Lichen studies in the western U.S. suggest that N deposition as low as 3-5 kg $ha^{-1}$ $yr^{-1}$ can cause significamt changes in lichen chemistry and lichen communities. However, based on previous studies in western North America (Fenn et al., 2003) and considering the throughfall deposition levels in the CRG, it is likely that other less sensitive ecosystem components and processes are also being impacted. Chronic N deposition of 10-25 kg N/ha/yr as reported in this study is within the range at which N fertilization type responses are expected, leading to increased N levels in soil, plants, and in soil leachate and runoff. Nitrogen cycling increases and the key N mobilization process of nitrification increases, leading to nitrate leaching losses from the forest. This syndrome of ecosystem responses to N deposition is often referred to as N saturation.

Soil acidification is caused by both N and S deposition as a gradual process. Increased nitrification rates, as described above, also results in soil acidification. As nitrate and sulfate is leached from soil, counter-balancing base cation leaching losses also increase, further leading to soil acidification. The risk to the ecosystem from soil acidification depends on the inherent buffering capacity of the soil. Most soils in western semi-arid ecosystems are well buffered compared to mesic forests. Thus, N enrichment effects are more common concerns in western forests exposed to chronic atmospheric deposition inputs. Further studies may be needed to ascertain the risk of soil acidification or depletion of base cations from forested sites in the CRG.

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Table 2. Precipitation amounts at weather stations and at deposition monitoring sites in the Columbia River Gorge[§].

| | Precipitation (cm; % of total in parentheses) | | | | | | |
|---|---|---|---|---|---|---|---|
| Dates | Bonneville Dam | | Hood River | | The Dalles | | |
| | | | | | | | |
| 10/1/03 to 10/28/03 (before collection) | 12.75 (7.3) | | 2.79 (4.9) | | 1.57 (4.6) | | |
| 10/29/03 to 3/9/04 (during collection) | 110.39 (62.8) | | 39.67 (69.2) | | 25.25 (73.7) | | |
| 3/10/04 to 9/30/04 (after collection) | 52.68 (29.9) | | 14.91 (26.0) | | 7.44 (21.7) | | |
| 2004 Water Year (Oct. 1, 2003 to Sept. 30, 2004) | 175.82 | | 57.38 | | 34.26 | | |
| | | | | | | | |
| | Deposition Study Sites | | | | | | |
| | MZ | Klick | 7MH | HTSP | WI | Celilo | MH |
| 10/29/03 to 3/9/04 | 95.23 | 28.95 | 28.17 | 22.03 | 22.16 | 18.08 | 20.36 |

[§]Precipitation data from the Integrated Plant Protection Center – Degree Day Calculator (http://ippc2.orst.edu/cgi-bin/ddmodel.pl). Locations of the weather stations are as follows:
Bonneville Dam: Bureau of Reclamation Agrimet
Bonneville Dam, WA – BNDW
Latitude: 45° 38' Longitude: 121° 55' Elevation: 24m

Hood River: Bureau of Reclamation Agrimet station
Hood River Experimental Station Oregon -- HOXO
Latitude: 45° 41' Longitude: 121° 31' Elevation: 174m

The Dalles: KDLS METAR Station
The Dalles Municipal Airport, WA
Latitude: 45° 38' Longitude: 121° 10' Elevation: 74m

Table 3. Comparison of nitrogen and sulfur deposition (kg/ha) in throughfall and bulk deposition at eastern versus western sites in the Columbia River Gorge[§].

| Ion | Western Sites | Eastern Sites | East:West Ratio |
|---|---|---|---|
| | | | |
| | Throughfall Deposition | | |
| $NO_3$-N | 5.11 | 5.94 | 1.16 |
| $NH_4$-N | 2.76 | 8.01 | 2.90 |
| $SO_4$-S | 2.18 | 2.97 | 1.36 |
| | | | |

[§]Western sites include Twin Tunnels high and low elevation and Catherine Creek high and low elevation sites. Eastern sites include Horsethief State Park, Wishram (bulk deposition only), Celilo and Maryhill sites. The Seven Mile Hill site was not included in these west-to-east comparisons because this site is higher in elevation and more exposed to fog deposition than the other sites and because this site is located approximately midpoint between the western and eastern sites. Data from the Mt. Zion site are not included either, because this is an extremely western site and strongly influenced by the Portland urban pollution plume. The Klickitat site was also excluded from the east/west comparison because it is located within a separate side drainage north of the main gorge and may not be exposed to the prinicipal air masses coming through the gorge to the same extent as the other sites.

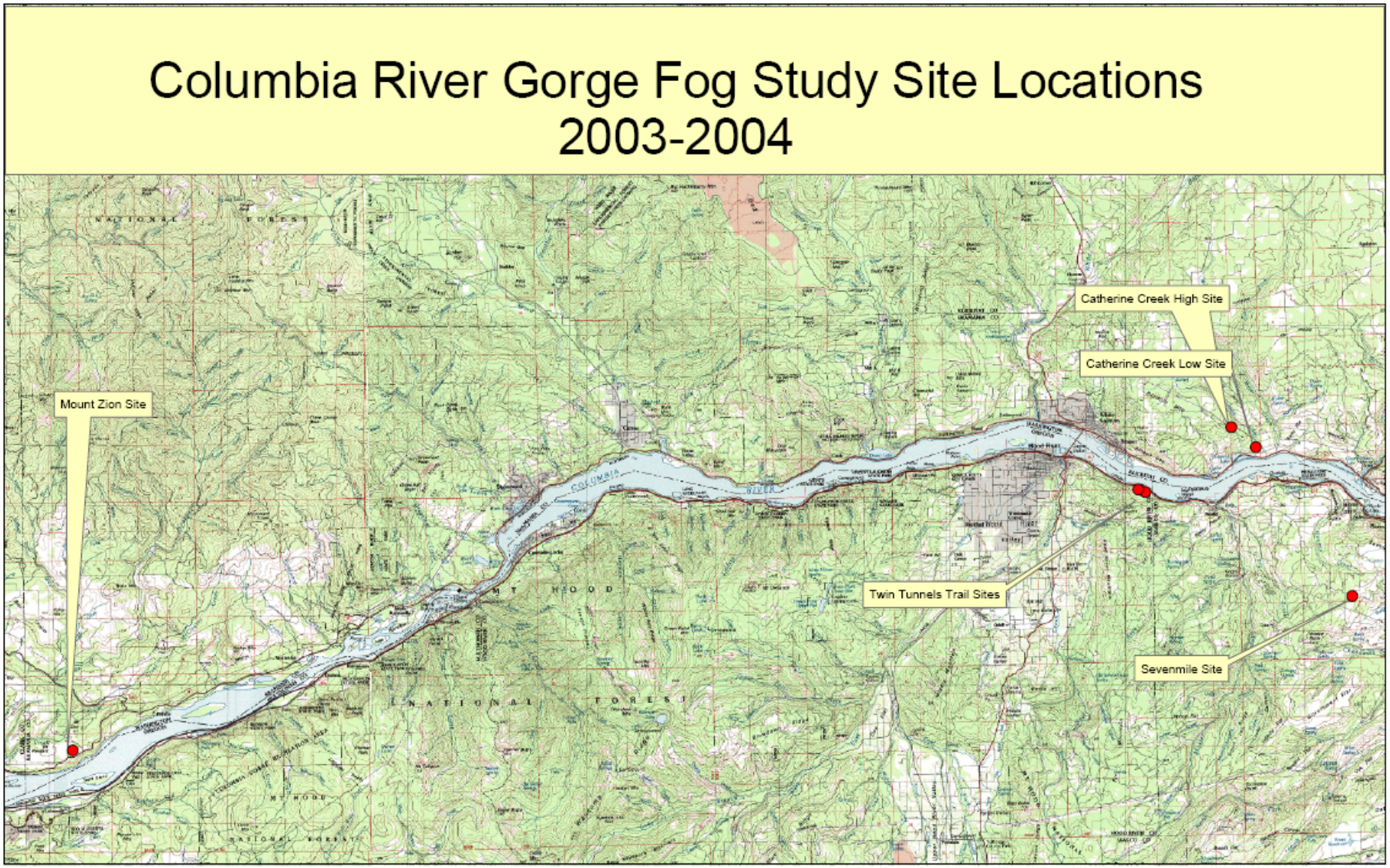


Fig. 1. Map showing the location of the atmospheric deposition monitoring sites in the Gorge.

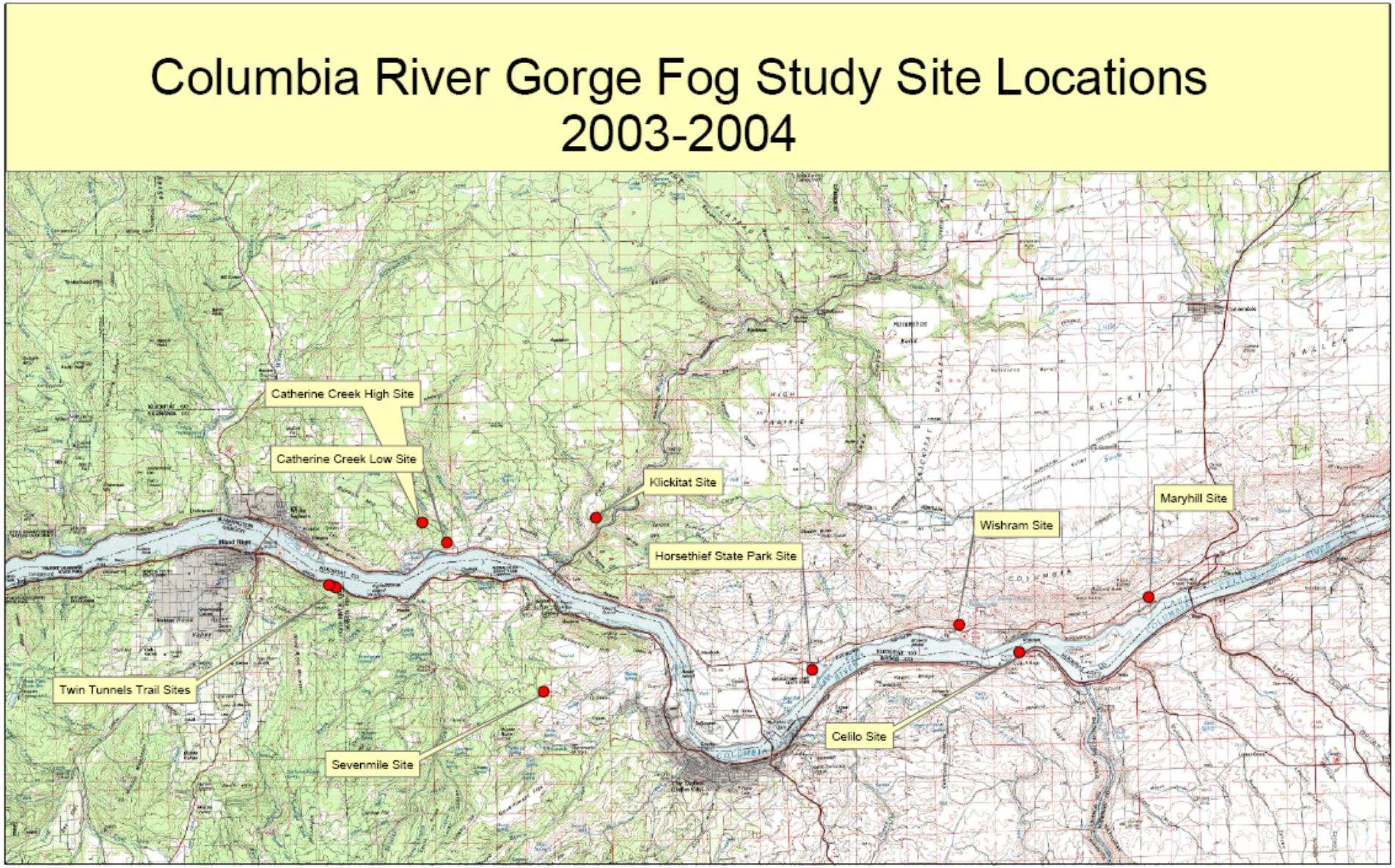


Fig. 1 continued.

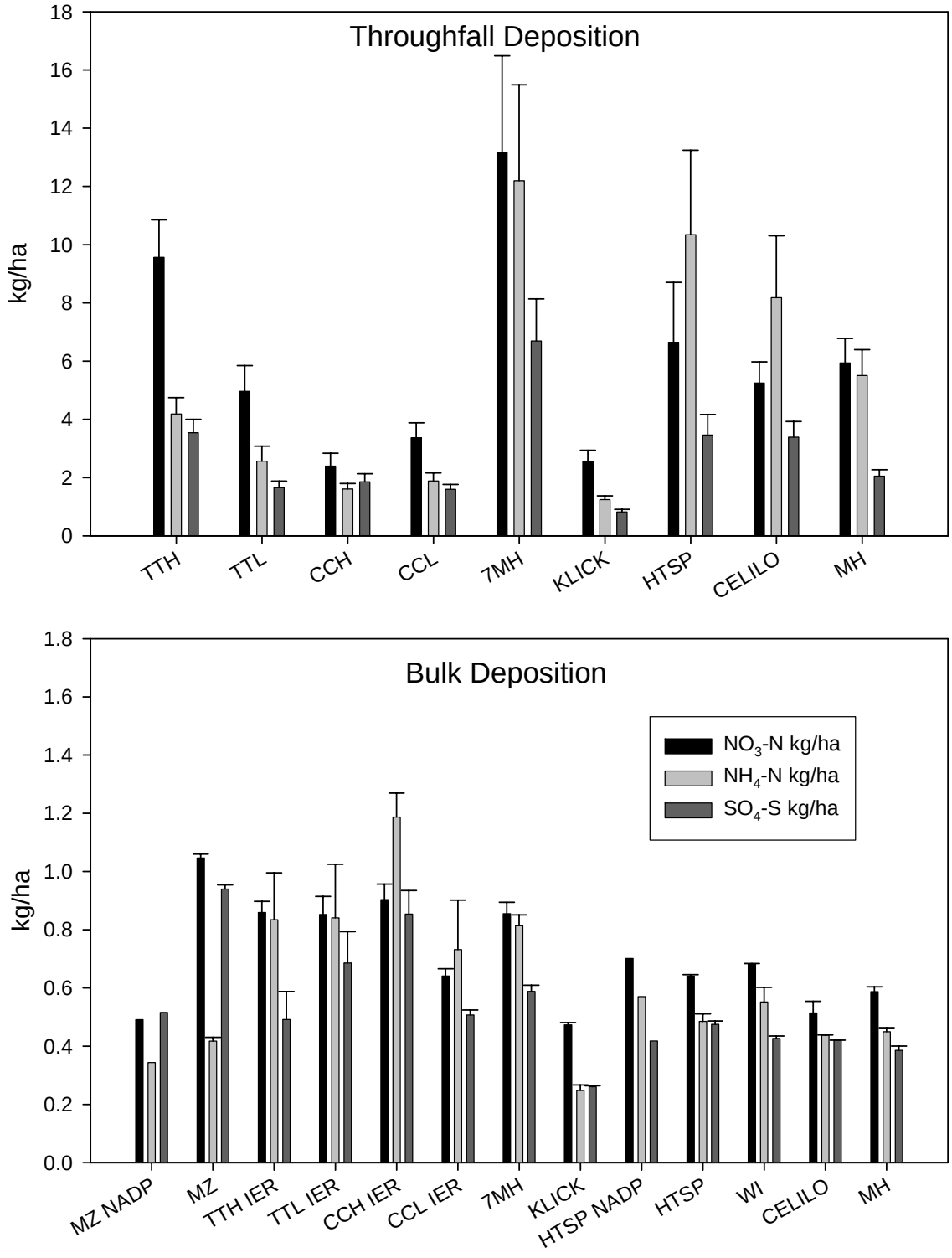


Fig. 2. Throughfall and bulk deposition fluxes during the 19 week monitoring period (October 2003 to March 2004). All throughfall samples were determined with ion exchange resin (IER) collectors and bulk deposition IER collectors were used for bulk deposition at the Twin Tunnels and Catherine Creek sites.

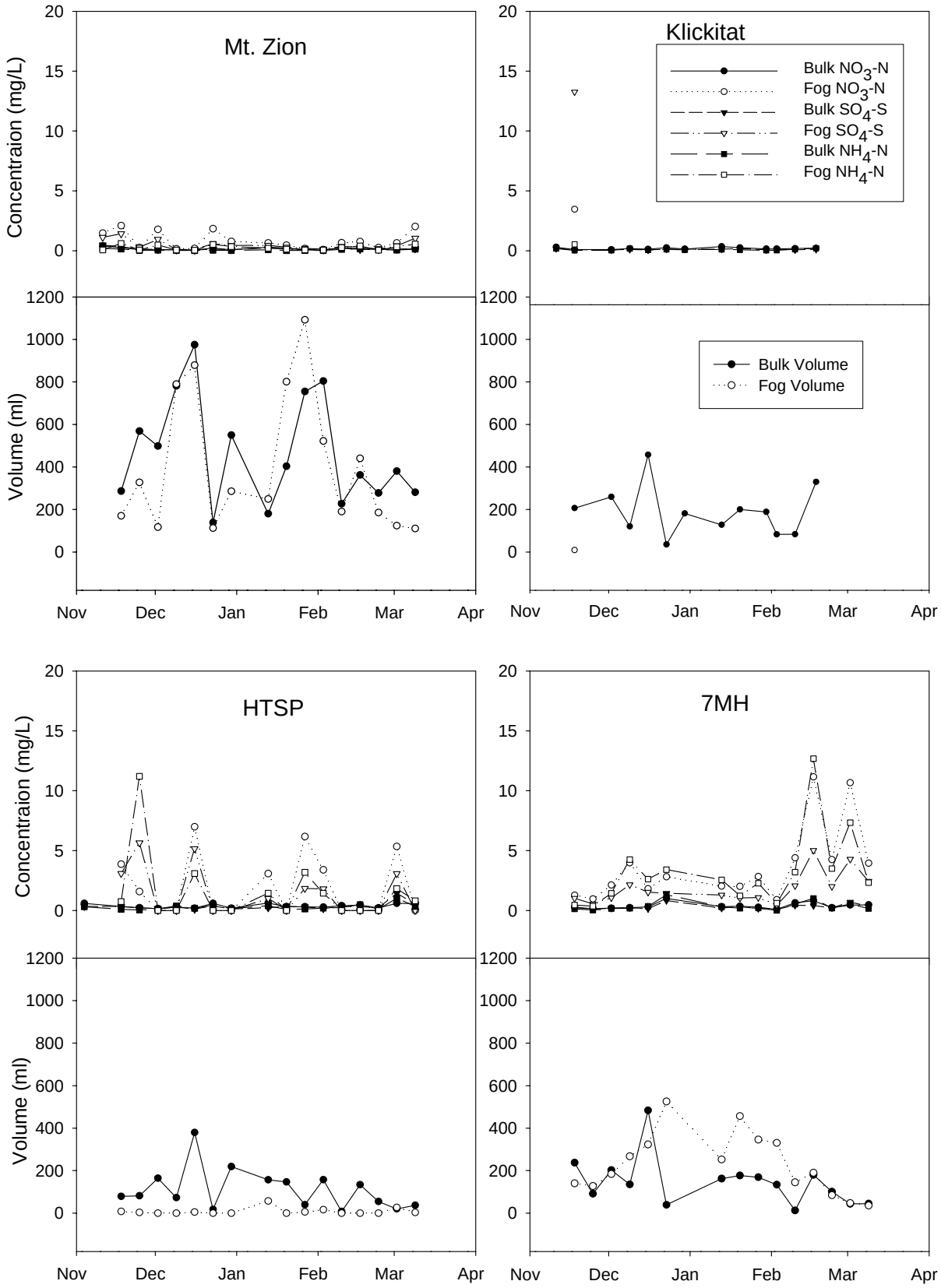


Fig. 3. Concentrations of nitrate, sulfate and ammonium in bulk deposition and fog samples.

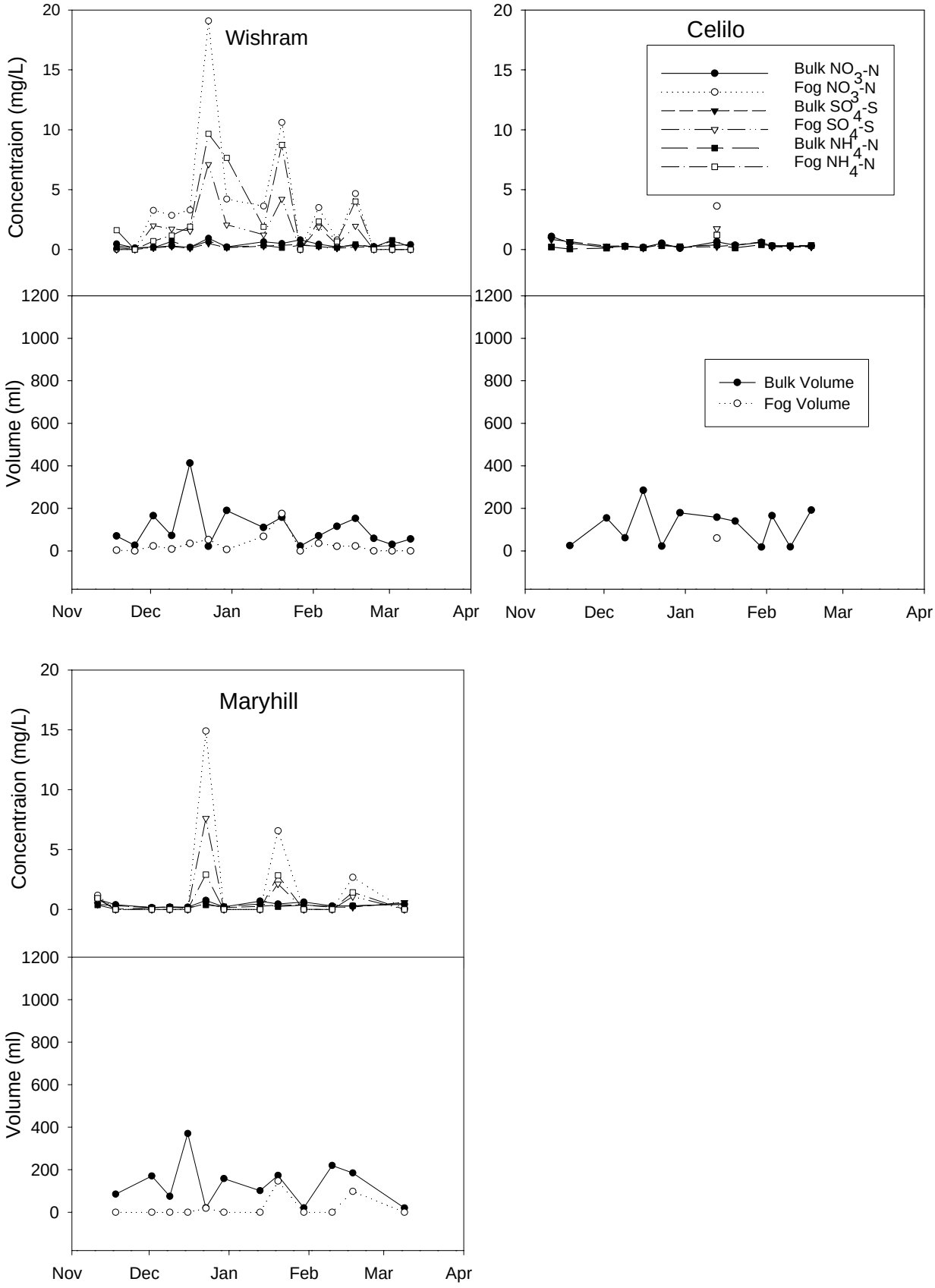


Fig. 3. Continued.

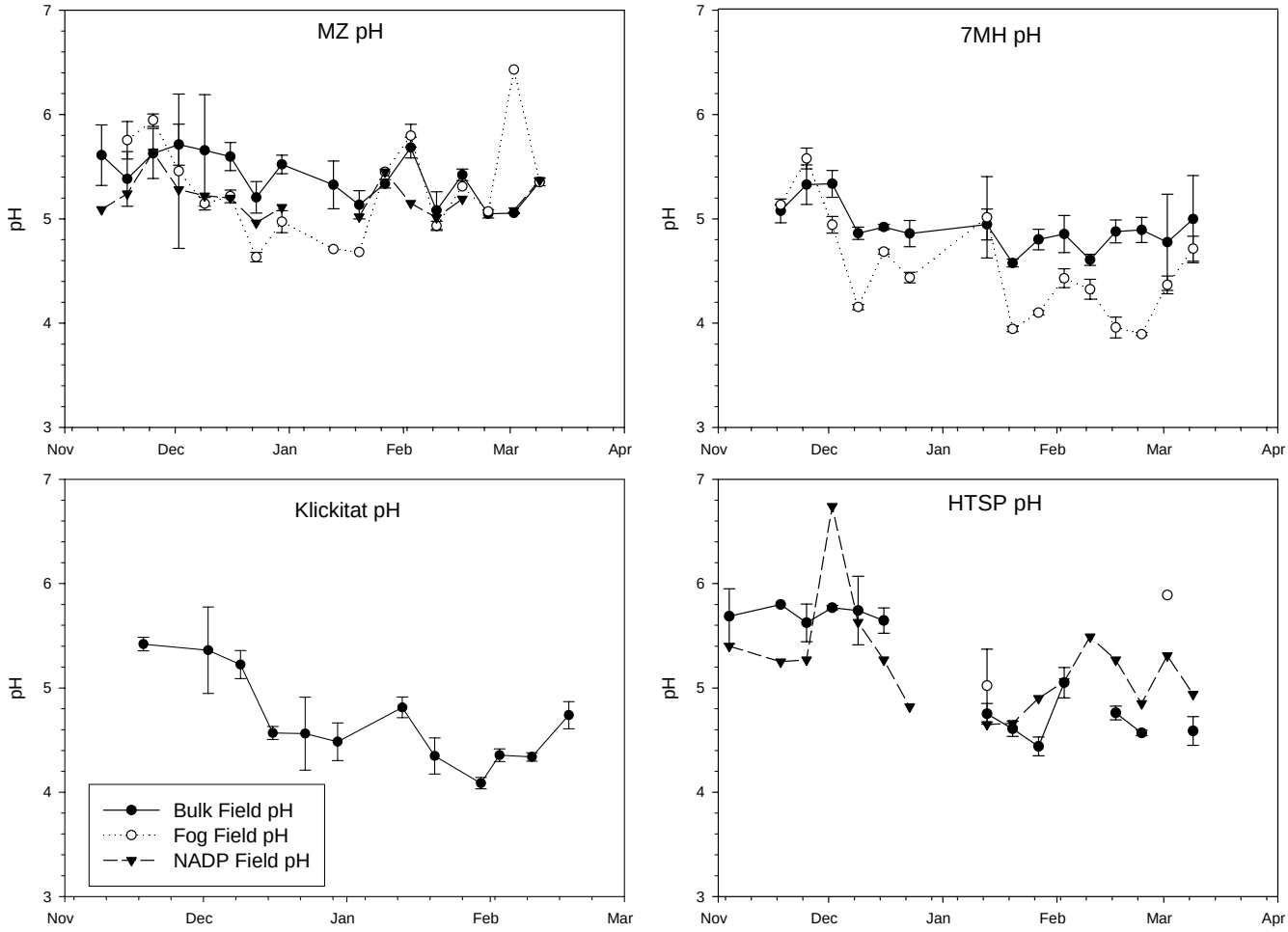


Fig. 4. The pH of fog or bulk precipitation samples. At Horsethief State Park (HTSP), an NADP style wet deposition collector was used and pH data is also shown for the NADP sampler.