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Assessing the Chemical and Biological Resilience of Lakes in the Cascade Range to Acidic Deposition

Joseph Eilers · Kellie Vache · Benn Eilers · Roger Sweets · Jack Cornett

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Abstract The potential for atmospheric deposition of sulfur and nitrogen to affect lakes in the Northwestern USA to cause lake acidification was assessed by examining four lakes extending from southern Oregon into the central Washington Cascades. The four lakes were dilute (conductivity 2.2 to 3.6 μS/cm), low ANC (−3 to 11 μeq/L) systems, located in subalpine to alpine settings in designated wilderness areas. The four lakes were cored, dated with ^{210}Pb and ^{14}C, and analyzed for sediment nutrients and diatom remains. Diatom-inferred changes in chemistry were made possible through an earlier project to create a diatom calibration set for the Cascades. The three southern lakes exhibited volcanic inputs of ash or tephra, but diatom stratigraphy generally showed only modest responses to these events. None of the lakes exhibited any recent trends in diatom-inferred pH. The most significant finding with respect to paleolimnology was that Foehn Lake, WA, was formed in the twentieth century (1930 ± 7 years), likely as a result of melting of an adjacent snowfield. Current deposition was estimated using the AIRPACT-3 system, and lake chemistry was simulated using the CE-QUAL-W2 hydrodynamic model that had been modified to represent acid-base chemistry. The model simulations showed that the three southern lakes in the transect were insensitive to increases of nitrogen and sulfur until simulated increases reached 300% of current levels. Foehn Lake showed simulated declines of pH and ANC beginning at 50% increases over current deposition of S and N. The three southern lakes are resistant to changes from atmospheric deposition and other disturbances because of long hydraulic residence times, allowing internal processes to neutralize acidic inputs.

Keywords Lake acidification · Lake formation · CE-QUAL-W2 · Atmospheric deposition · Paleolimnology

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J. Eilers (✉) · B. Eilers
MaxDepth Aquatics, Inc., Bend, OR 97703, USA
e-mail: j.eilers@maxdepthaq.com

K. Vache
Department of Biological and Ecological Engineering, Oregon State University, Corvallis, OR 97331, USA

R. Sweets
Department of Biology, Indianapolis University, Indianapolis, IN 46227, USA

J. Cornett
Cosray Technology Centre, MyCore Scientific, Inc., Deep River, ON K0J 1P0, Canada

1 Introduction

It has been known for several decades that elevated levels of sulfur and nitrogen deposition can cause changes to lakes and streams, largely through acidification. In addition, other causes can include climatically induced acidification (Webster et al. 1990; Koinig et al. 1998) or contamination from deposition of organic compounds (Heit et al. 1981; Fernandez et al. 2002) and toxic metals such as mercury (Krabbenhoft et al. 2002). Most of the early effects of atmospheric deposition on freshwater ecosystems were reported for eastern North America and northern Europe, where the presence of a large number of low-alkalinity waterbodies and high rates of sulfur and nitrogen deposition resulted in widespread response. As researchers broadened the geographic scope of their investigations, they found that aquatic systems in other regions were also sensitive to anthropogenically derived compounds in deposition. Studies in the central Rocky Mountains and the Sierra Nevada ranges illustrated that even modest increases in deposition of sulfur and nitrogen can cause measureable changes to some dilute freshwater systems (Clow et al. 2002; Williams and Tonnessen 2000; Baron et al. 2000; Wolfe et al. 2003).

In the Northwest USA, deposition has remained low, and most of the data suggests that acidification of lakes has not occurred to any significant extent (Nelson 1991). The most detailed estimates of atmospheric deposition of sulfur and nitrogen for the region were generated for national parks in the state of Washington which range from 1.0 to 3.2 kg S ha^{-1} $year^{-1}$ and 0.5 to 1.2 kg N ha^{-1} $year^{-1}$ (Fenn et al. 2013). Deposition rates for Oregon are likely equal to or less than those measured in Washington. However, population projections forecast major increases in growth for the region, prompting concerns among federal resource managers that increased population growth, and the accompanying economic activity, could increase emissions of sulfur and nitrogen high enough to promote damage to sensitive resources. In addition, the major growth of economic activity in Asia, particularly in China, raises concerns that long-distance transport of pollutants could impact the Northwest. Recent estimates indicate that China is constructing a new coal-fired power plant every week (Lelyveld 2016). Thus, forces within and beyond the Northwest may result in increased deposition of sulfur and nitrogen to the region.

To address this concern, the USDA Forest Service initiated a study to ascertain the potential risks of increased deposition to lakes in the Northwest. Rather than focus on one specific site for this analysis, the federal resource managers elected to study the likely response of sensitive aquatic systems across a likely north-south gradient of deposition chemistry. The objectives of the study were to describe current lake conditions, place the current conditions in a long-term context through paleolimnology, and forecast a range of possible responses to different levels of atmospheric inputs of sulfur and nitrogen through numerical modeling.

2 Site Description

The study area is the Cascade Range extending from southern Oregon up through Washington (Fig. 1). The four study sites are located on the west slope or near the crest of the Cascades. Indeed, two of the study lakes, Notasha and Scout, border the Pacific Crest Trail. Summit Lake is located northwest of Mt. Rainier across the Carbon River. Foehn Lake is also west of the Cascade crest in King County east of Seattle. Information on the location and attributes of the study lakes are shown in Table 1. Summit, Scout, and Notasha lakes are located in volcanic terrain, and Notasha and Scout lakes appear to be ice-block melt basins from the recent glacial retreat. Lake Notasha is south of Crater Lake (N), and proximate to two volcanic peaks, Pelican Butte (SE) and Mt. McLoughlin (SW). Scout Lake is located at the base of Mt. Jefferson, which last reported an eruption in the late Pleistocene, although a nearby cinder cone erupted about 950 AD (Smithsonian Global Volcanism Program, www.volcanoe.si.edu). Rock types within these volcanic areas are typically basaltic andesite. The depth of Summit Lake (50.9 m) suggests that forces other than glaciation may have contributed to its morphometry. Foehn Lake is located on the Snoqualmie batholith and the rock types are tonalite and granodiorite (Tabor et al. 1993). Foehn Lake is at the edge of the tree line, whereas the other three lakes have light (Summit, Scout) to heavy (Notasha) tree cover nearby.

The study lakes were selected to represent the range of chemistry found in a N-S transect in the Cascade Range in designated wilderness areas. Lakes were selected that had low acid neutralizing capacity (ANC) because these lakes would be most susceptible to the effects of atmospheric deposition. The program began sampling in 2004 with Greenridge Lake as the northernmost lake in the series. This lake was discontinued because of its relatively high ANC and was substituted with Foehn Lake in 2005.

3 Methods

Lakes were accessed on foot, and sampling was conducted from inflatable craft over the deep areas of the

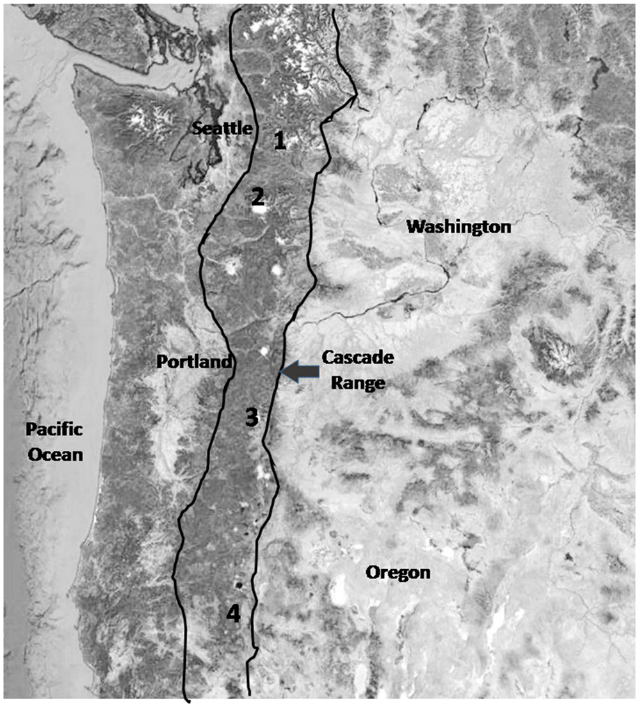

Fig. 1 Study lakes where *1* = Foehn, *2* = Summit, *3* = Scout, and *4* = Notasha

lakes. Bathymetric maps for lakes Notasha and Summit were available from earlier studies (Eilers et al. 1996; Eilers et al 1998), and new maps were generated for Scout and Foehn lakes using a custom-made lightweight echosounder linked with a GPS device. Similarly, paleolimnological reconstructions had been completed for lakes Notasha and Summit prior to the onset of this investigation, but sediment cores were collected from Scout and Foehn lakes. Several cores were collected from the deeper areas of both lakes to verify that maximum penetration was achieved. The cores from Scout Lake were collected using a modified gravity core (Glew 1991) equipped with a 5-cm diameter polycarbonate tube. The cores from Foehn Lake were collected by diving and forcing the core tube into the sediment. The sediment samples from Scout Lake were sectioned

Table 1 Location and attributes of the four study lakes

Attribute	Units	Notasha	Scout	Summit	Foehn
Elevation	m	1836	1780	1658	1737
Latitude	d.d	42.5680	44.70865	47.03994	47.56711
Longitude	d.d	- 122.2097	- 121.81013	- 121.83147	- 121.25857
National forest	–	Rogue-Winema	Willamette	Mt. Baker-Snoqualmie	Mt. Baker-Snoqualmie
Wilderness	–	Sky lakes	Mt. Jefferson	Clearwater	Alpine lakes
Surface area	ha	2.7	3.1	8.82	0.43
$Depth_{max}$	m	10.6	9.7	50.9	5.4
$Depth_{mean}$	m	3.6	4.4	21.2	2.2
Volume	m^3	9.6×10^4	1.18×10^5	1.87×10^6	9.57×10^3
Precipitation	cm	160	230	230	300
HRT[a]	year	1.4	1.5	8.4	0.9

[a] Hydraulic residence time (τ) is traditionally calculated as $\tau = V/Q$ where V = lake volume and Q = discharge from lake. However, since these lakes do not have a surface outflow, we represented hydraulic residence time for comparative purposes as V/Precip adjusted for estimated evaporation. This will likely underestimate actual values of τ

at the lake into 1-cm intervals, whereas the sections from Foehn Lake were divided into 0.5-cm intervals. Cores were analyzed for percent water, total nitrogen (TN), and total phosphorus (TP) at the Soils Physics Laboratory, Oregon State University. Age of sediment was determined by ^{210}Pb for the upper organic fractions of the sediment and using ^{14}C dating for selected intervals deeper in the core. The ^{210}Pb dating was conducted by MyCore Scientific, Inc. (Deep River, Ontario) using the methods described by Cornett et al. (1984). The ^{14}C dating was conducted by Beta Analytic using radiocarbon methods (http://www.radiocarbon.com/beta-analytic.htm). Diatom remains from the sediments were analyzed at Indianapolis University using methods described by Sweets et al. (1990). Diatom-inferred pH down-core estimates were generated by using a diatom calibration set for the Cascades (Online Resource 1). Diatom results from the sediment cores have been archived in the Neotoma Paleoecology Database (http://www.neotomadb.org).

Samples for analysis of water chemistry were collected from over the deepest portion of the lake by lowering Nalgene bottles to about 0.5 m below the surface and capping the samples underwater. Samples were returned to shore where they were typically packed in snow for the return hike. Samples for analysis of nutrient concentrations were conducted at the Central Analytical Laboratory on the campus of Oregon State University (http://ccal.oregonstate.edu/). Analysis of the major ions of samples was conducted at the USFS/USGS Laboratory in Ft. Collins, CO. Aliquots for phytoplankton community composition were preserved in Lugol's solution and analyzed by Aquatic Analysts, Inc., Friday Harbor, WA. Vertical tows using a 200-μm mesh were used to collect samples for analysis of zooplankton community composition. These were preserved on-site using ethanol and analyzed for community composition by ZP Taxonomic Services, Lakewood, WA.

Modeled nitrogen and sulfur deposition values were produced using the 3rd generation Air Indicator Report for Public Access and Community Tracking (AIRPACT-3) modeling system. AIRPACT-3 is a 3-dimensional eulerian air quality forecast modeling system that has at its core the CMAQ photochemical transport model, and uses meteorological inputs from the MM5 meteorological model and emissions from the SMOKE emissions model. A full description of the AIRPACT-3 system is provided in Chen et al. (2008) and details of the deposition modeling are available from the Washington State University Laboratory for Atmospheric Research (www.lar.edu/res_reg-airq.html).

The modeling approach uses a two-part strategy comprised first of calibration and validation and second, the use of the calibrated models in evaluation of potential responses to changing patterns of deposition. The period over which model calibration was developed was selected based primarily on the availability of both input and evaluation data sets. The 2-year period from January 2004 to December 2005 was selected, because this period included the most complete input data for the study lakes. We focus most of the results representing current conditions during this period of time.

CE-QUAL-W2 (referred to here as W2) incorporates a large suite of water quality variables; however, the water quality components of the model have primarily been developed for use in eutrophication studies. As such, some aspects of water quality as it relates to acidification studies are not included in the standard version of W2. These include the base cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (SO_4^{2-} and Cl^{-}). Additionally, in the standard version of W2, alkalinity is treated as a conservative value, which is not satisfactory for assessing potential effects of atmospheric deposition. To apply the model in this project, the above items were addressed through expansion of the code base (Online Resource 2). Specific modifications included the use of the generic constituent features to simulate the missing ions and modification of the code to utilize a full ion balance in the calculation of alkalinity ($C_B - C_A$). The model computes water chemistry of the lake as a function of equations based on the water column. However, because the model is calibrated to observed water chemistry, it indirectly incorporates interactions with the sediment.

4 Results and Discussion

4.1 Current Conditions

Secchi disk visibility extended to the bottoms of Notasha, Scout, and Foehn lakes on all sampling visits. Secchi disk transparency was reported at 17 and 20 m for Summit Lake in 2004 and 2006, respectively. There was no apparent color to any of the lakes that suggested the presence of appreciable amounts of humic compounds. The high transparency of the lakes allowed for direct viewing of much of the lake substrate. Beyond the rocky shores, lakes Notasha and Scout had substrate that consisted of fine-grained sediment with little overlying flocculent material. Abundant large woody debris extended from the shore to deeper areas of Lake Notasha. The bottom of Foehn Lake was comprised mostly of large boulders with small patches of accumulated sediment. Although we could not see to the lake bottom throughout Summit Lake, the areas from shore to about 10 m were comprised of exposed rock. Deeper in the lake, the bottom was covered by bryophytes, which was confirmed for those areas beyond 20 m by sampling with sediment core samplers and dredges.

Lake chemistry for the four study lakes was stable during the study period and showed that all four lakes are extremely dilute (Table 2) with specific conductance values less than 4 μS/cm. The measured pH values correspond well to those expected given these measured ANC values. pH values for the four lakes decrease from south to north. The measured ANC for lakes Notasha and Scout are positive, whereas those for Summit and Foehn lakes are slightly negative. Comparison of the measured ANC with calculated alkalinity ($C_B - C_A$) shows that the measured values are consistently less than the calculated values. This may reflect uncertainty in the analytical measurements at these low ionic strengths. Alternatively, unmeasured organic anions could be present in sufficient concentrations to cause the calculated alkalinity values to overestimate the actual neutralizing capacity, yet at low enough concentrations that they do not impart a humic tint to the lake water.

The concentrations of base cations are lowest for Foehn Lake, indicating little watershed input of weathering products to this lake. Among the base cations, Na^+ is greatest for Summit Lake. This, combined with the high Cl^-, indicates a greater input of marine aerosols in Summit Lake compared to the other sites. Sulfate concentrations are low for the two Oregon lakes but slightly higher for Summit and Foehn lakes. Examination of sea-salt corrected concentrations of sulfate (SO_4^*) shows that most of the sulfate in these lakes is not derived from marine sources. All four lakes have similarly low concentrations of phosphorus. However, the lakes differ with respect to nitrogen; the Washington lakes have significantly lower concentrations of total nitrogen. Based on N/P ratios, these lakes are P-limited. However, concentrations of inorganic nitrogen are often near detection limits suggesting that the lakes may be limited by nitrogen or co-limited by both N and P.

Table 2 Major ion and nutrient chemistry measured in the four study lakes. Values represent the average of available measurements

Analyte	Units	Notasha	Scout	Summit	Foehn
pH	sa	6.16	6.06	5.71	5.50
ANC	μeq/L	11.1	7.8	−0.8	−3.1
Conductivity	μS/cm	2.52	2.24	3.64	3.25
Cations					
H	μeq/L	0.70	0.87	1.96	4.25
Ca	μeq/L	9.58	7.93	7.40	6.39
Mg	μeq/L	6.46	3.74	3.81	2.02
Na	μeq/L	5.37	7.89	10.73	5.98
K	μeq/L	2.30	2.88	0.20	0.77
NH_4	μeq/L	0.13	0.15	0.11	0.05
Anions					
F	μeq/L	0.68	0.05	0.11	0
CL	μeq/L	4.41	4.25	8.89	3.23
NO_3	μeq/L	0.01	0.01	0	0
SO_4	μeq/L	1.81	1.73	6.34	9.20
Derived					
SO_4[a]	μeq/L	1.34	1.28	5.41	8.86
C_B	μeq/L	23.71	22.45	22.14	15.15
C_A	μeq/L	7.21	6.33	15.33	12.43
$C_B - C_A$	μeq/L	16.50	16.12	6.81	2.72
Nutrients					
TP	μg/L	3.7	2.7	3	2
PO_4	μg/L	0.7	0.3	1	1
TN	μg/L	77	63	40	30
NO_3	μg/L	0.3	0.3	0	0
NH_4	μg/L	2.3	2.7	2	1

[a] SO_4 = sea-salt corrected concentrations of sulfate

Phytoplankton abundance as indicated by algal biovolume was low in all four lakes. Results for phytoplankton, zooplankton, and benthic invertebrates are provided in Supplemental Information D. Algal biovolume is extremely low in Summit Lake and surprisingly low in Scout Lake. Algal biovolume was more moderate in Foehn Lake, perhaps because of its shallow depth. Algal cell density followed a generally similar ranking as biovolume among the four lakes, although cell density was comparatively higher in lakes Notasha and Scout because of high numbers of small taxa. For lakes with multiple phytoplankton samples, Notasha and Scout, the dominant taxa remained relatively stable from year to year. The dominant group in Lake Notasha was the dinoflagellates, with green algae as subdominants. In

Scout Lake, the dinoflagellates were also important, although there was a more balanced population of green algae and chrysophytes. Summit Lake phytoplankton was totally dominated by diatoms, whereas Foehn Lake was dominated by dinoflagellates. Chlorophyll *a* concentrations were low in all four lakes, although again Summit Lake exhibited the lowest observed values. Concentrations in the other three lakes were similar with median values between 1 and 2 μg/L.

Community composition and abundance of zooplankton varied greatly among the study lakes. Lake Notasha had an abundant and diverse zooplankton population characterized by high densities of cladocerans, copepods, and rotifers. Although most of the cladocerans were relatively small, Lake Notasha had *Daphnia rosea*, a large cladoceran present in all samples from this lake. The zooplankton population in Scout Lake was comprised of low densities of cladocerans but high densities of large diaptomid copepods (*Diaptomus kenai?*) and abundant rotifers. Zooplankton density and diversity was very low in Summit and Foehn lakes. Cladocerans were rare in both of these lakes, although copepods were moderately abundant in Summit Lake. Rotifers were also sparse in both Summit and Foehn lakes.

The benthic macroinvertebrate populations in all four study lakes are depauperate based on these qualitative samples. Only Scout Lake exhibited a reasonable abundance of chironomids, with six genera and 198 individuals collected in the three Eckman dredge samples. The extensive mats of bryophytes over the substrate of Summit Lake may have hindered collection of additional invertebrates because of the difficulty in penetrating the vegetation. A sediment core tube was used to sample benthic invertebrates in Foehn Lake, but despite repeated attempts, only one individual (a chironomid) was collected.

Summit and Foehn lakes differ from the Oregon study lakes in several respects. Both Summit and Foehn lakes exhibit concentrations of sulfate that appear elevated above natural conditions. The sulfate likely has neutralized several microequivalents of ANC, putting both lakes on the cusp of acidification. Most of this sulfate is nonmarine in origin, and in Summit Lake, it was demonstrated through isotopic analysis that the majority of the sulfur was derived from atmospheric deposition (Eilers et al. 1998).

Summit Lake differs from the other study lakes in several respects. The lake is closest to marine waters, it is at the lowest elevation, it is deep, and it has a dense mat of bryophytes over much of the bottom. The proximity to marine waters and lower elevation makes it more likely that it will receive higher concentrations of marine aerosols. This explains the comparatively high chloride levels in the lake and the higher proportion of marine-derived sulfate. However, marine-derived sulfate still accounts for only 15% of the sulfate concentrations in the lake. The considerable depth of Summit Lake results in a long hydraulic residence time and thus increases the likelihood that in-lake processes can neutralize acid inputs (Baker et al. 1988). The long hydraulic residence time also has a dampening effect on short-term changes in deposition. The large biomass of bryophytes present in Summit Lake, most likely the dominant biological feature of the system, makes it possible that these plants influence acid-base chemistry of the lake. Bryophytes are known to act as ion exchangers by assimilating divalent cations and releasing H^+ and organic anions (Clymo 1967; Glime et al. 1982).

Foehn Lake is slightly acidic (albeit within the error of the ANC analysis), shallow, and apparently newly formed. Sulfate ions may have neutralized several microequivalents of ANC. Given the low concentrations of base cations in Foehn Lake, only modest levels of sulfur deposition are necessary to acidify the lake. Because Foehn Lake is shallow, it has a shorter hydraulic residence time and is more susceptible to short-term changes in external factors. The minimal accumulation of sediment offers relatively little buffering of external inputs. The apparent youth of the exposed watershed terrain results in low weathering rates, thus minimizing neutralization of incoming acids. The lake is extremely depauperate from a biological perspective, with few zooplankton crustaceans or benthic invertebrates present. The one sample of phytoplankton collected from Foehn Lake was dominated by two species of dinoflagellates.

4.2 Historical Conditions (Paleolimnology)

The sediment cores from the four lakes were physically different, although the modern accumulated sediment represented the top 3 to 5 cm in all lakes (Table 3). The longest sediment core was collected from Lake Notasha where penetration beyond 39 cm was not possible using a push-rod piston corer. The base of the core was uniform light gray tephra. The organic matter immediately above this layer yielded a ^{14}C date of 6600 YBP which was slightly younger than the reported eruption of Mt. Mazama dated at 7627 ± 150 cal year B.P. (Zdanowicz

Table 3 Summary and description of sediment composition in the four study lakes

Attribute	Notasha	Scout	Summit	Foehn
Core descriptions	Largely organic with base of dense tephra	Upper sediments organic; lower half tephra	Top of core covered with bryophytes; two pumice layers below the modern sediment	Fine-grained material interspersed with pebbles; base layer of ash or sand
Length of core (cm)	39	18	20	3
Depth of modern (ca 1870) sediments (cm)	3–4	4–5	4	3
Date of core base (YBP)	6600	1000	3355	76
Surface SAR (g/m^2/year)	NA	77	172	125
Average modern SAR (g/m^2/year)	NA	52	73	173

SAR sediment accumulation rate

et al. 1999). Crater Lake is only 36 km north of Lake Notasha and the massive eruption likely explains the substantial deposition of tephra in the lake. Lake Notasha underwent a substantial shift in diatom stratigraphy about 3000 YBP but has remained relatively stable since then.

Scout Lake sediments have remained stable for the last 1000 years judging from the unchanging diatom stratigraphy, relatively uniform chemistry, and unaltered sediment accumulation rate (SAR). The layer of tephra in Scout Lake did not appear to be as compacted as that observed in Lake Notasha as it was possible to penetrate up to 10 cm into the ash with the gravity corer. The ^{14}C date of 1000 YBP for the interface between the organic matter and the tephra corresponds with a published date of the last eruption in the area of 950 AD from the South Cinder Peak cone located about 15.6 km south of Scout Lake (http://www.volcano.si.edu/world/volcano.cfm). It is unclear if the tephra layer in Scout Lake is derived from this event or from an eruption from other volcanic vents in the area.

The Summit Lake sediments were noteworthy in that the top of the sediments was covered with bryophytes and there were two intervals of the core with pumice. The uppermost pumice layer was below the modern sediments. This pumice layer likely corresponds with the Mullineaux (Mullineaux 1974) “C” layer of Holocene tephra events from Mt. Rainier which he dated at 150 YPB. Again, the diatom stratigraphy indicated no significant change in diatom taxa throughout the core, despite inputs from two volcanic eruptions.

Foehn Lake sediments were limited to a depth of only 3 cm and it was the only study lake without noticeable volcanic material present. The six sections analyzed showed no significant change in diatom stratigraphy, although the sediment dating did suggest that the interval at 2.5 cm below the surface exhibited an increase in sediment accumulation rate. The most noteworthy aspect of the core is that ^{210}Pb activity did not reach baseline levels as observed in other Cascade sediments. By substituting what appears to be a reasonable range of background activity, the base of the core dates from between 1924 and 1937. This indicates that Foehn Lake is a newly formed lake, likely the product of melt from what had been a long-lived snowfield.

The paleolimnological data suggest that the chemistry and biology of all four study lakes have been relatively stable over the last century (Fig. 2). Diatom community composition in the sediment cores and the DI-inferred down-core values show no significant sign of change. Even Lake Notasha, which has a dense forest surrounding the lake that has likely experienced repeated forest fires, showed no indication that the major ion chemistry had fluctuated to any measureable degree in the last 3000 years. Lakes Notasha, Scout, and Summit experienced moderate to high rates of camping pressure as evidenced by trails, campsites, and damaged vegetation and yet no effects to the lakes were evident. These same three lakes have also been stocked with trout during portions of the twentieth century, and whatever biological changes may have occurred were insufficient to be detected in this study. This excludes possible predation of native amphibians through the introduction of trout (Kats and Ferrer 2003). Stratigraphy of the dominant diatoms shows relatively little discernable pattern through the recent century (Fig. 2). The most common taxa, *Aulacoseira distans* and *Psammothidium marginulatum*, accounted for about 50% of the observed frustules in the lakes, with the exception of Lake Notasha where the dominant genus was *Pinnularia.* Taxa observed to be associated elsewhere in the western

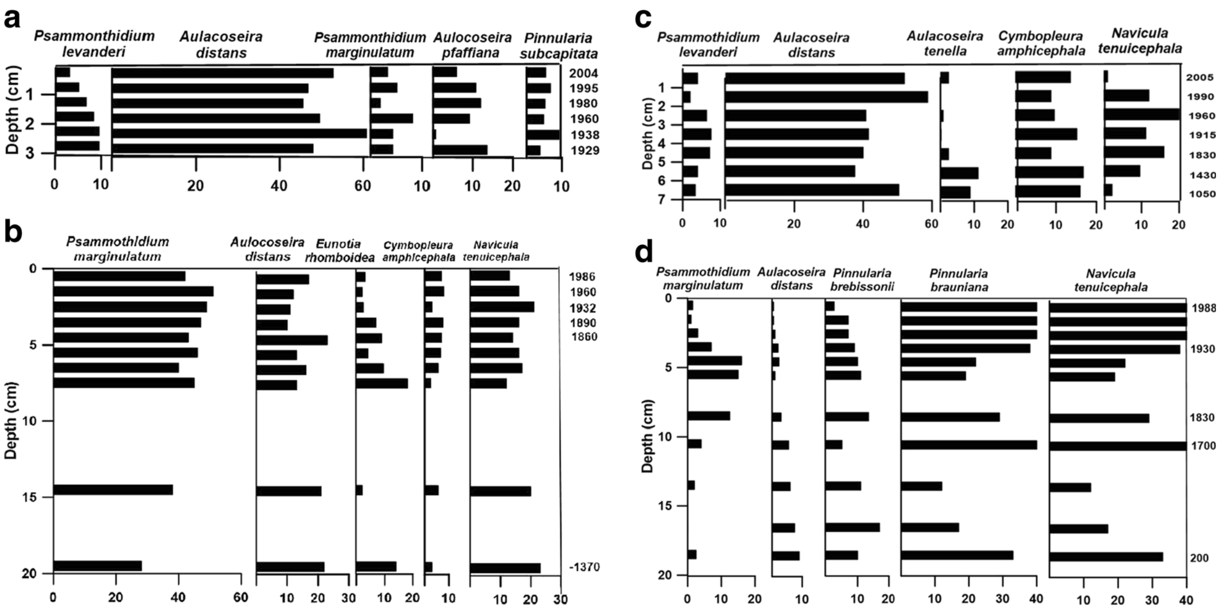

Fig. 2 Dominant sediment diatoms from the four study lakes by depth and estimated date of sediments: **a** Foehn, **b** Summit, **c** Scout, and **d** Notasha. The sediment results for Lake Notasha have been truncated mid-core. Complete diatom results for this lake are available elsewhere (Eilers et al. 1996)

USA with increasing nitrogen deposition, *Asterionella formosa* and *Fragilaria crotonensis* were virtually absent from the sediments of these four lakes.

4.3 Forecasted Lake Response to Changes in Atmospheric Deposition

The model runs based on current deposition were used to calibrate to current conditions in all four lakes. The inputs of sulfur and nitrogen were then increased for each lake as combinations of both sulfur and nitrogen and nitrogen alone. The forecasted lake responses for lakes Notasha, Scout, and Summit indicated relatively little change in lake pH until sulfur and nitrogen deposition had been increased by 300% (Figs. 3, 4, 5, and 6). This is less surprising for Lake Notasha and Scout Lake where there still are modest concentrations of ANC (~10 μeq/L) present. An earlier modeling analysis illustrated that seepage lakes such as these can be highly resilient to inputs of sulfur and nitrogen because of internal lake processes associated with relatively long-residence time systems (Baker et al. 1988). However, Summit Lake has virtually no measureable ANC and yet the model suggests that it will remain stable under moderate increases in sulfur and nitrogen deposition. Again, this may be attributed largely to its considerable depth (50 m) and long hydraulic residence time. Although complex sediment interactions were not included in the modeling, there is a large biomass of bryophytes present in Summit Lake, and these plants may exert more control of the acid-base chemistry on this lake than those derived from external inputs.

Foehn Lake, as expected, shows the greatest response to inputs of sulfur and nitrogen. Factors that likely contribute to this are its shallow bathymetry, the high percentage of exposed bedrock in the lake, and its sparse sediments. This lake appears to be less than a century old based on the ^{210}Pb dating. The diatom community composition in the sediments shows no indication of any significant change during this period. Although there is the expectation that deposition of sulfur and nitrogen has increased in the last 100 years downwind of the Olympia-Seattle urban corridor, results suggest that the lake has not responded. The average nonmarine sulfate concentrations in Foehn Lake are indicative of some anthropogenic inputs, yet the sediment diatoms have remained stable. The modeling scenarios predict that a measureable decline in pH for Foehn Lake will not occur unless sulfur and nitrogen deposition rates are increased by at least 50 to 100% over current levels. Thus, there is a congruence of the paleolimnological data and the modeling forecasts for Foehn Lake. Clearly, the most significant finding regarding Foehn Lake is that it is recently formed. Mote (2003) reported

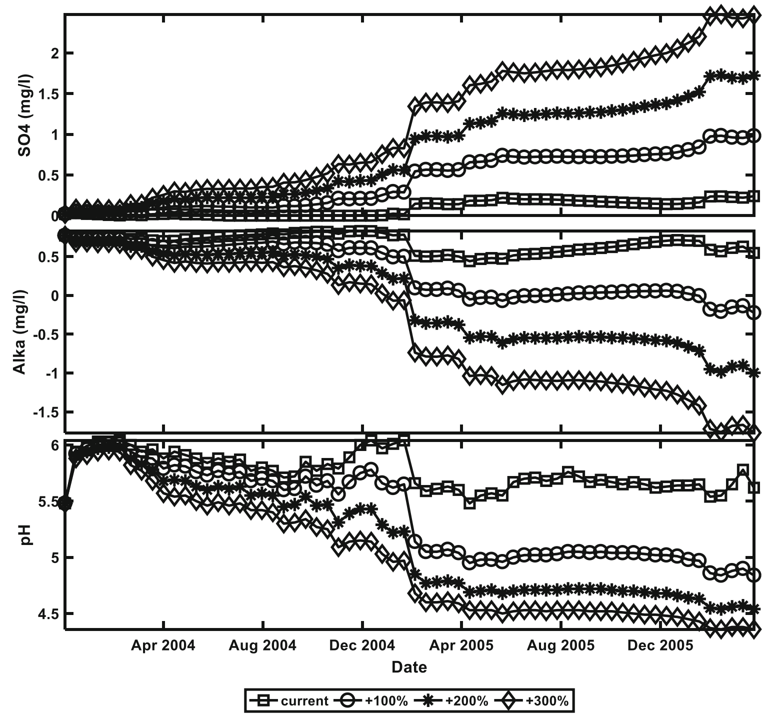

Fig. 3 Model simulations for Lake Notasha, Oregon. The four different time series represent simulated conditions under current conditions and three difference scenarios, assuming a 100%, 200%, and 300% increase in cumulative deposition over the 2-year simulated timeframe. The increase in SO_4 (and associated decrease of alkalinity and pH) between December and April of the second simulated year results from the modeled deposition data, which included elevated deposition of SO_4 and NO_3 during a relatively wet period of time

that there had been an increase in mean annual air temperature in the Pacific Northwest between 1920 and 2003 of 0.7 to 0.9 °C and that the warmest year during that period was 1934. Mote et al. (2003) forecast additional increases in mean annual temperature for the region with additional consequences for vegetation,

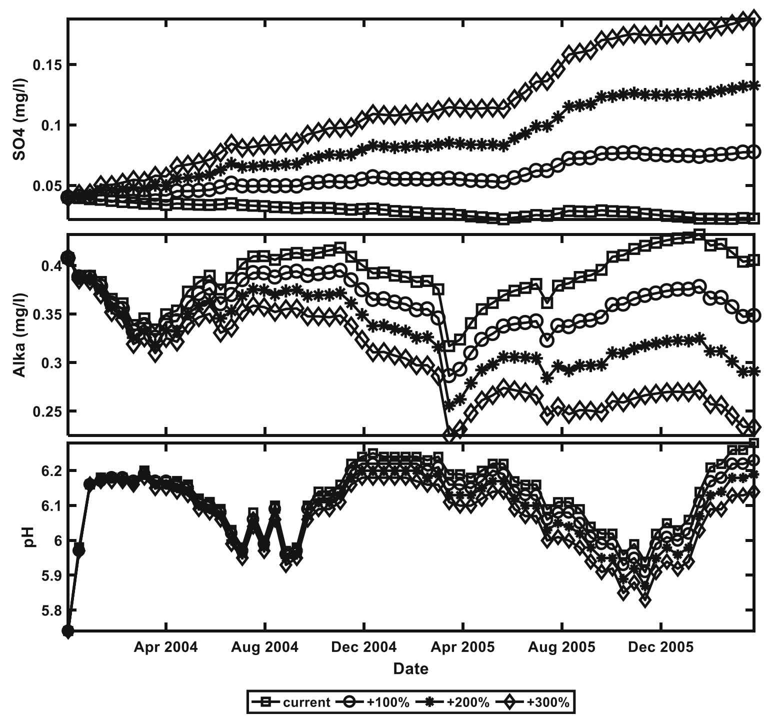

Fig. 4 Model simulations for Scout Lake, Oregon. The four different time series represent simulated conditions under current conditions and 3 difference scenarios, assuming a 100%, 200% and 300% increase in cumulative deposition over the 2 year simulated timeframe

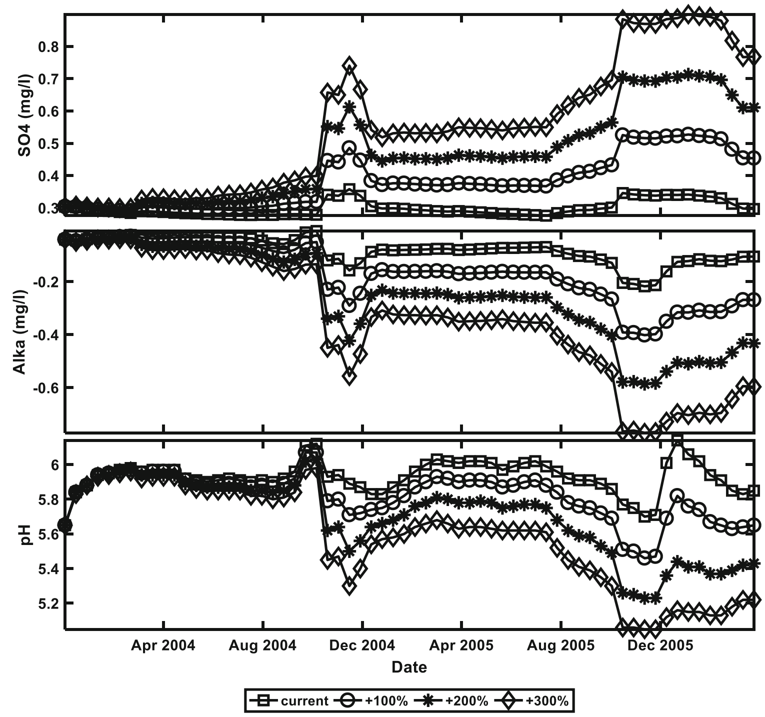

Fig. 5 Model simulations for Summit Lake, Washington. The four different time series represent simulated conditions under current conditions and three difference scenarios, assuming a 100%, 200%, and 300% increase in cumulative deposition over the 2-year simulated timeframe. The two spikes of SO_4 (and associated decreases of alkalinity and pH) result from the modeled deposition data, which included elevated deposition of SO_4 and NO_3 during those periods

hydrology, and fisheries. These observations of historical climate trajectories, along with modeled climate futures, are consistent with the idea that Foehn Lake was recently formed as a consequence of decreased winter snowpack associated with increased air temperatures.

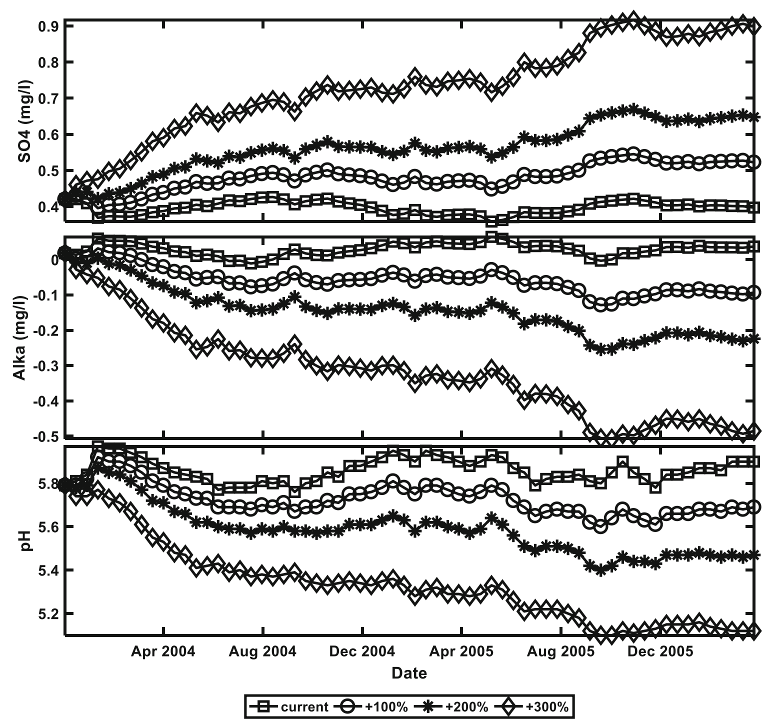

Fig. 6 Model simulations for Foehn Lake, Washington. The four different time series represent simulated conditions under current conditions and three difference scenarios, assuming a 100%, 200%, and 300% increase in cumulative deposition over the 2-year simulated timeframe

Saros et al. (2005) observed increases in the diatoms *A. formosa* and *F. crotonensis* in the sediments of oligotrophic alpine lakes in the Beartooth Mountain Range (Montana-Wyoming), which they attributed to increases in nitrogen deposition. Our Cascade study lakes did not exhibit similar changes in the sediment diatom composition, indicating that there has been no discernible aquatic response yet to possible increases in deposition of nitrogen. In addition, the Cascade study lakes showed little change in acid-base chemistry to increases in simulated deposition of nitrogen only. Once again, it may be that these longer-residence time seepage lakes allow for sufficient internal processing to assimilate inputs of nitrogen without posing a major risk to either the acid-base status of the lakes or to their trophic status. An examination of the stoichiometry of the water chemistry in these four study lakes indicated that they were likely phosphorus-limited systems, and therefore, they may be relatively insensitive to moderate increases in nitrogen deposition. The sediment intervals used for the diatom reconstructions in the three southern lakes are rather coarse for assessing recent changes on a decadal level over the last century. However, the similarity in diatom communities between the top of the cores and the deeper intervals suggests that the conclusions regarding lack of acidification are sufficiently robust. For Foehn Lake, the six sediment intervals represent the 80 years or so of the lake existence and should be adequate for characterizing trends.

The issue of establishing critical loads of atmospheric deposition to protect resources in sensitive areas of the USA appears to be gaining attention in recent years. Blett et al. (2014) describe an effort to develop national-scale critical loads for the USA. Their pilot study offered critical load estimates for surface waters and forest acidity. Shaw et al. (2014) focused on generating critical loads for lakes in the Sierra Nevada using a steady-state water chemistry model (SSWC) developed by Henriksen et al. (1992) and Henriksen and Posch (2001). The results indicated that some study lakes were still recovering from elevated acidic deposition in earlier decades. Despite the extremely low ANC of these four Cascade study lakes, they appear to be able to withstand substantially greater loads of acidic deposition than lakes in the Sierra Nevada and Rocky Mountains. We attribute this to the different hydrologic regime of these Cascade lakes and their greater opportunity for internal processes to neutralize acidic anions, as was observed in Florida lakes (Baker et al. 1988). Of the four study lakes, only Foehn Lake showed a modeled response to simulated moderate increases in deposition of acid anions. Low acid neutralizing capacity is certainly a prerequisite for a high degree of responsiveness to atmospheric deposition, but hydrology, specifically hydraulic residence time, is perhaps of greater importance in determining the responsiveness of Cascade lakes to atmospheric pollutants.

Deposition of acidic precursors has been a major focus of concern for lakes and streams in the eastern portion of the USA and northern Europe. However, some investigators have expressed concern for deposition of nutrients as a mechanism for altering the chemistry and biota of aquatic resources. Bergstrom and Jansson (2006) in a study of lakes in 42 regions in Europe and North America suggested that phytoplankton biomass has increased in a number of these systems as a consequence of inorganic nitrogen deposition. This conclusion is consistent with the findings of Baron et al. (2000) and Saros et al. (2005) who observed evidence of phytoplankton community shifts that they attributed to increased deposition of inorganic nitrogen. Saros et al. noted that the elevated N deposition was expressed as increased abundance of the diatoms *A. formosa* and *F. crotonensis*. These are taxa often associated with eutrophication in productive lakes, but were nevertheless observed to be increasing in oligotrophic alpine lakes in the Rocky Mountains. A study of nitrogen deposition effects on diatom communities in 12 lakes from three areas of Washington found little to no evidence of response from atmospheric deposition of nitrogen (Sheibley et al. 2014). Four of the lakes were located in the Mt. Rainier National Park located immediately south of Summit Lake, and none of these lakes exhibited significant changes in diatom community composition in the sediments. Sheibley et al. concluded that one lake in the Olympic National Park, Hoh Lake, had been affected by atmospheric changes in nitrogen deposition and estimated a critical load of 1.0 to 1.2 kg N ha^{-1} $year^{-1}$ for this particular lake. This is similar to the critical load of 1.4 kg N ha^{-1} $year^{-1}$ estimated by Saros et al. (2011) for lakes in the eastern Sierra Nevada and the Greater Yellowstone ecosystem. The importance of nitrogen deposition to this and other lakes in the region was confirmed by Williams et al. (2016) who conducted in situ bioassays on nine lakes in the three Washington national parks (four lakes of which overlapped with those studied by Sheibley et al.) and concluded that all lakes were either N-limited or co-limited by P. Although bioassays and paleolimnological evidence indicates that some lakes in the western USA are responsive to relatively low rates of nitrogen deposition, it is somewhat surprising that at least some of the lakes in this study did not show evidence of diatom shifts that have been determined elsewhere to be associated with increases in nitrogen deposition. The model results using W2 indicate that there is ample opportunity for assimilation and reduction of nitrogen in at least the three southernmost lakes (Summit, Scout, Notasha). The lake in our study set most likely to respond to increases in atmospheric deposition of nutrients or acidic anions is Foehn Lake and it has shown no trends in diatom community composition during the twentieth century. A possible explanation is that because it is so shallow ($Z_{max} = 5.4$ m), the potential biological activity in the sediments effectively dampens lake response to atmospheric change. We know from the work by Arnett et al. (2012) that for shallow lakes in the Rocky Mountains, the degree of agreement between the diatom-inferred nitrate values and lake nitrate concentrations was poor. It is unknown whether lake depth or confounding factors such as increased annual air temperature (or associated duration of ice cover) are related to the absence of changes in diatom community composition for these Cascade lakes.

Another component of global disruption of atmospheric chemistry is the increase in CO_2 concentrations. Recent modeling studies suggest that increased availability of CO_2 promotes primary production in aquatic ecosystems, especially low-alkalinity freshwater (Schippers et al. 2004). We were unable to detect responses in these four study lakes, although the simulated responses generated by Schippers et al. were generally expressed at higher CO_2 concentrations than we have experienced to date.

The most demonstrable effect of climate on these Cascades study lakes is the formation of a lake in the last century as a consequence of melt from a former snow field. Melting glaciers continue to form new lakes elsewhere around the globe (Bajracharya and Mool 2010), but glaciers have not been present at this elevation in this portion of the Washington Cascades for millennia. Furthermore, no fine sediments, typical of glacial melt, were present in the sediments of Foehn Lake that would have indicated a source from glaciers. The formation of this new lake from snow melt presents an opportunity to observe lake ontogeny and associated biological changes. Presently, Foehn Lake is a highly depauperate system and it will be interesting to observe if the likely biological increase in diversity will precede or follow changes in lake chemistry.

5 Conclusions

Although these four low ANC lakes are considered highly sensitive to acidification and other forms of atmospheric inputs, the hydrology of three of the four lakes appears to make them highly resistant and resilient to alteration from atmospheric inputs. Even major natural upsets from volcanic eruptions and forest fires caused only relatively short-term deviations in major chemical and biological attributes. Only the shorter residence time system, Foehn Lake, exhibits a moderate sensitivity to changes in atmospheric inputs. The three southern lakes with longer hydraulic residence times were likely formed during the retreat of glaciers more than 10,000 years ago. However, the northernmost lake, Foehn Lake, was apparently formed during the much more recent melt of a long-standing snowfield and is less than a century old. Unlike the other study lakes, its flora and fauna are depauperate. The study showed that the application of a widely used hydrodynamic model, CE-QUAL-W2, could be modified to test the response of lakes that are hydrologically connected weakly to their watersheds and allow investigators to better incorporate internal lake processes for lake studies. It would also allow investigators studying lakes in other hydrologic settings (e.g., runoff-driven "drainage" lakes) to evaluate lake response to atmospheric change in a dynamic framework rather than relying solely on steady-state models or statistical techniques.

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