Assessing the Use of Diatom-Based Critical Loads of Nitrogen Deposition in Lakes from Three National Parks in Washington State

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Abstract

The goal of this study was to document whether or not lakes in national parks in Washington have exceeded critical levels of nitrogen (N) deposition causing changes to lake diatom communities, as observed in other Western States. We measured atmospheric N deposition, lake water quality, and sediment diatoms at our study lakes. Water chemistry analyses indicated that our study lakes were ultra-oligotrophic, with ammonium and nitrate concentrations often equal to or less than detection limits with low specific conductance (<100 µS/cm) and acid neutralizing capacities (<400 µeq/L). Rates of total inorganic N deposition during the summer at all our sites ranged from 0.6 to 2.4 kg of N per ha/yr and were variable both within and across the national parks. Diatom assemblages increased in relative abundances of *Asterionella formosa* and *Fragilaria tenera* in a single sediment core from Hoh Lake [Olympic National Park (OLYM)] from 1969 to 1975, although these species were not observed at the remaining nine sites. These diatom species are known to be indicative of N enrichment, which allowed for the development of an empirical critical load of N deposition, or threshold level, where changes in diatom communities were observed. We used modeled precipitation for Hoh Lake and annual inorganic nitrogen concentrations from a nearby National Atmospheric Deposition Program station to calculate elevation-corrected N deposition for 1980–2009 at Hoh Lake. An exponential fit to this data was hindcasted to the 1969–1975 time period and we estimated a critical load of 1.0–1.2 ±0.01 kg N per ha/yr for wet inorganic N deposition for this lake. This project was completed in cooperation with the National Park Service through the USGS-NPS water quality partnership program.

Site Selection

Site selection was based on previous work at these lakes and on the following hypothesis:

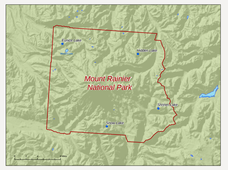
- Elevation is important; high elevation lakes have less alkalinity in general, and are more susceptible to the effects of nitrogen deposition.
- Location in the park is important; some areas get more deposition than others. Therefore, a good spatial distribution will capture a range in nitrogen deposition.
- Lakes in basins with large numbers of red alder (*Alnus rubra*) should be avoided; nitrogen fixing plants will make interpretation of nitrogen deposition data difficult. Alder trees are less likely at high elevation sites.

From this information, the following list of site selection criteria was established:

- Elevation above 4,000 feet.
- Above tree line, or minimal forested area around lake.
- Maximum depth greater than 10 feet.
- Area smaller than 25 hectares.
- Oligotrophic status.
- Low acid neutralizing capacity /conductivity lakes preferred.
- No fish (low densities are acceptable).
- No major influences from wildlife (for example, minimize disturbance of lake sediment).
- Talus slope preferred for resin collectors deployment.
- Try to overlap with existing park projects (for additional data and possible coordination of field efforts).
- Try to minimize popular visitor sites.
- Within each park:
  - Lakes should span a gradient of elevation.
  - Lakes should have good spatial representation.

Study Sites

Four lakes from each of the three national parks (fig. 1) in Washington State were selected for this project based on the previously outlined selection criteria. Lakes with a good range of elevation and spatial coverage within each park were selected. A summary of physical characteristics for each lake are listed in table 1. NOCA has the largest elevation gradient at about 2,200 feet, with OLYM having the smallest at about 600 feet. NOCA also contains the largest and deepest of lakes studied.



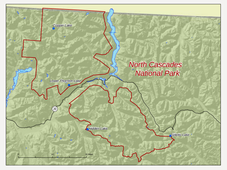


Figure 1. Location of study lakes in the three national parks in Washington State.

Table 1. Physical properties of study lakes.

Study lake	Elevation (feet)	Area (hectare)	Maximum depth (feet)
Mount Rainier National Park (MORA)			
Eunice	5,360	5.3	65
Hidden	5,930	2.1	23
Shriner	4,889	1.7	11
Snow	4,680	2.4	32
North Cascades National Park (NOCA)			
Copper	5,263	5.2	67
Hidden	5,733	25.0	258
Stiletto	6,795	4.0	85
Thornton	4,486	27.3	108
Olympic National Park (OLYM)			
Heather	5,215	0.4	23
Hoh	4,539	7.4	49
Milk	4,708	1.1	46
PJ	4,540	0.8	21

Lake Chemistry

Water-quality samples were collected from August 2009 to August 2010 at a depth of 1 ft over the deepest part of the lake. Waters generally had low specific conductivity and were low in nutrients (table 2). In addition, orthophosphate concentrations were less than detection limits (<0.001 mg/L of P) and chlorophyll-*a* concentrations were less than 1.0 µg/L at most sites (data not shown). Nutrient data were used to calculate the mass ratios of DIN (ammonium plus nitrate) to total phosphorus (TP) of the surface water at the time of core collection. This DIN:TP ratio has been shown to be a good indicator of nitrogen (N) or phosphorus (P) limitation of lakes because it provides a useful measure of the nutrient supply available to phytoplankton (Bërgström, 2010). Using one-half of the detection limit for censored data in table 2, DIN:TP mass ratios were 1.5 or less (indicating N-limitation; Bërgström, 2010) at all lakes in Mount Rainier National Park (MORA), at Hoh and Milk Lakes in Olympic National Park (OLYM), and at Copper Lake in North Cascades National Park (NOCA); although Hidden, Lower Thornton, and Stiletto Lakes at NOCA, and Heather Lake at OLYM indicated possible colimitation of N and P. None of the study lakes indicated strict P limitation (DIN:TP > 3.4; Bërgström, 2010) at the time of sampling.

Table 2. Lake surface water-quality data from study lakes.

[ANC, acid neutralizing capacity; DIN, dissolved inorganic nitrogen; TP, total phosphorus; µS/cm; microsiemens per centimeter at 25 degrees Celsius; µeq/L, microequivalents per liter; --, no sample; < less than]

Lake name	Specific conductance (µS/cm)	pH	ANC (µeq/L)	Ammonia (mg/L as N)	Nitrate plus nitrite (mg/L as N)	Total phosphorus (mg/L as P)	DIN:TP
Mount Rainier National Park (MORA)							
Eunice	7.5	6.51	30	<0.01	0.002	0.012	0.7
Hidden	15.8	6.67	46	<0.01	0.001	0.004	1.5
Shriner	--	--	--	--	--	--	--
Snow	12.9	5.41	10	<0.01	<0.001	0.006	0.9
North Cascades National Park (NOCA)							
Copper	5.6	6.14	26	<0.01	<0.001	0.004	1.4
Hidden	5.6	6.66	30	<0.01	0.001	0.002	2.8
Lower Thornton	10.3	6.88	50	<0.01	0.004	0.003	3.0
Stilletto	9.4	6.29	90	<0.01	0.006	0.007	1.6
Olympic National Park (OLYM)							
Heather	71.0	7.15	374	<0.01	0.007	0.005	2.4
Hoh	62.2	7.52	394	<0.01	0.001	0.007	0.9
Milk	37.2	7.16	284	<0.01	<0.001	0.004	1.4
PJ	--	--	--	--	--	--	--

Bulk Atmospheric Deposition of Nitrogen in Summer

During summer 2008, bulk atmospheric N deposition was determined at each lake using an ion-exchange resin collector (Fenn and others, 2002). We installed five collectors around the shoreline of each lake. Bulk deposition generally was variable within and across each national park (table 3). Averaged N deposition was highest at NOCA, lowest at OLYM, and in between NOCA and OLYM at MORA.

Table 3. Summary of bulk deposition data collected during summer 2008.

[NH_4-N, data are site averages ± standard deviation. At Shriner Lake, one resin column was retrieved, no standard deviation was calculated. (kg/ha)/yr, kilograms per hectare per year]

Lake name	Days deployed	NH_4-N [(kg/ha)/yr]	NO_3-N ([kg/ha]/yr)	NH_4+NO_3 ([kg/ha]/yr)	SO_4-S ([kg/ha]/yr)
Mount Rainier National Park (MORA)					
Eunice	85	1.07 ± 0.10	0.91 ± 0.12	1.97 ± 0.19	1.90 ± 0.44
Hidden	76	0.58 ± 0.17	0.49 ± 0.18	1.07 ± 0.34	1.18 ± 0.38
Shriner	86	0.95	0.56	1.51	1.05
Snow	71	0.51 ± 0.14	0.58 ± 0.12	1.09 ± 0.22	1.45 ± 0.44
Park average	--	0.73 ± 0.28	0.65 ± 0.22	1.38 ± 0.48	1.48 ± 0.49
North Cascades National Park (NOCA)					
Copper	66	1.06 ± 0.21	1.20 ± 0.11	2.27 ± 0.32	2.28 ± 0.40
Hidden	59	1.01 ± 0.07	1.02 ± 0.22	2.02 ± 0.19	1.71 ± 0.58
Lower Thornton	72	1.10 ± 0.21	1.32 ± 0.19	2.42 ± 0.27	2.10 ± 0.70
Stiletto	71	0.46 ± 0.41	0.73 ± 0.24	1.19 ± 0.40	1.12 ± 0.27
Park average	--	0.93 ± 0.34	1.09 ± 0.29	2.02 ± 0.55	1.84 ± 0.65
Olympic National Park (OLYM)					
Heather	65	0.25 ± 0.15	0.45 ± 0.11	0.70 ± 0.10	0.86 ± 0.49
Hoh	68	0.49 ± 0.25	0.48 ± 0.15	0.97 ± 0.30	2.33 ± 0.69
Milk	80	0.49 ± 0.07	0.55 ± 0.12	1.04 ± 0.13	1.31 ± 0.32
PJ	60	0.25 ± 0.11	0.34 ± 0.04	0.59 ± 0.07	1.25 ± 0.17
Park average	--	0.37 ± 0.19	0.46 ± 0.13	0.83 ± 0.42	1.44 ± 0.70

Diatom Results

We analyzed top and bottom slices of sediment cores from 10 of the 12 lakes in this study to search for known diatom indicators of N enrichment (*Asterionella formosa* and *Fragilaria tenera*). We observed these indicators in only one lake (Hoh Lake, OLYM). To investigate further, 4 of the 10 lake cores were analyzed for historical diatom communities and dated using lead-210 and cesium-137 isotopes (fig. 2). Hoh Lake was the only site to clearly show shifts in diatoms caused by N-enrichment, and this shift took place around 1969–1975.

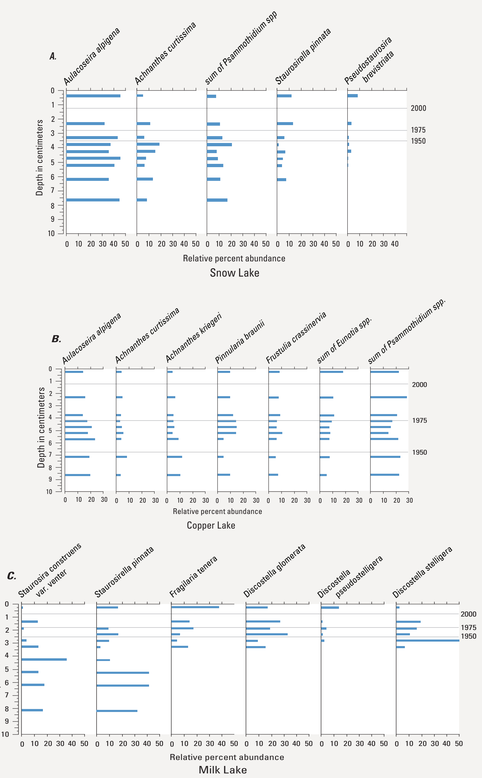


Figure 2. Depth profiles showing relative percent abundance of major diatom species from (*A*) Snow Lake, (*B*) Copper Lake, (*C*) Milk Lake, and (*D*) Hoh Lake. Note that for Hoh Lake, *Pseudostaurosira brevistriata* and *Staurosira construens var. venter* were only counted down to a depth of 10 centimeters.

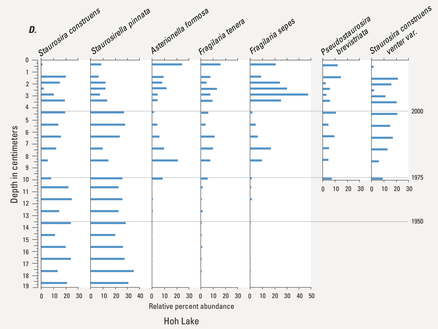


Figure 2. —Continued.

Hindcasting Deposition to Determine Critical Load

Historical wet N deposition collected at Hoh Ranger Station [National Atmospheric Deposition Program station WA14] was combined with parameter-elevation regressions on independent slopes model (PRISM) precipitation data for Hoh Lake to estimate elevation-corrected wet N deposition from 1980 to 2009 (fig. 3). We fit this data with an exponential curve with and without a preindustrial anchor point (0.5 kg of N per ha/yr; Baron, 2006; Saros and others, 2010) and estimate a critical load for wet N deposition at Hoh Lake of 1.0 to 1.2 kg of N per ha/yr.

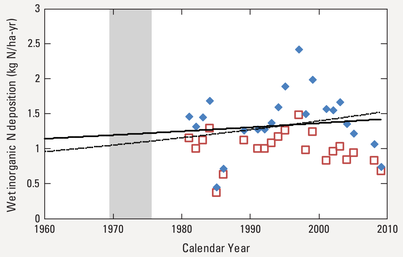


Figure 3. Annual wet inorganic nitrogen deposition from National Atmospheric Deposition Program station WA14 (Hoh Ranger station) (open squares) and elevation-corrected annual deposition (solid diamonds) using parameter-elevation regressions on independent slopes model (PRISM) precipitation data at Hoh Lake and National Atmospheric Deposition Program annual N concentrations of inorganic N from station WA14. Lines represent the exponential fit to the elevation-corrected data with (dashed line) and without (solid line) a preindustrial anchor point of 0.5 kilograms of nitrogen per hectare per year. Shaded region represents the time period where diatom changes in the Hoh Lake sediment core were observed and a critical load was calculated.

Conclusions

At Hoh Lake, shifts in diatom community compositions since 1969–1975 are indicative of N enrichment in the lake system. These community shifts allowed for the development of a critical load estimate for this lake ranging from 1.0 to 1.2 ± 0.01 kg of N per ha/yr for wet inorganic N. This study shows that critical loads estimated from diatoms are lower than those calculated in previous studies for other ecosystem endpoints (such as lichens, terrestrial plants, or lake acidification), suggesting that diatom-based critical loads can be used to provide broad ecosystem protection for lake ecosystems. Future work is needed to investigate the cause of N enrichment at Hoh Lake. In addition, research into Pacific Northwest-specific diatom indicators is warranted. To date, most work on developing diatom-based critical loads comes from the Rocky and Sierra Nevada Mountains; however, it is possible that other diatoms are sensitive to changes in N in the Pacific Northwest that we do not know about at this time.

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Eunice Lake | Hidden Lake | Shriner Lake | Snow Lake — Mount Rainier National Park
Copper Lake | Hidden Lake | Stilleto Lake | Thornton Lake — North Cascade National Park
Heather Lake | Hoh Lake | Milk Lake | PJ Lake — Olympic National Park