Final Report
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Project Title: **Inferring Critical Nitrogen Deposition Loads to Alpine Lakes of Western National Parks and Diatom Fossil Records**

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PROJECT SUMMARY

Shifts in algal (diatom) composition in alpine lakes are frequently the first indication of ecological perturbations in these systems. Of the major disturbances affecting alpine lakes, enhanced atmospheric nitrogen (N) deposition is one of the primary concerns. Previous research using sedimentary diatom profiles identified a critical N load of 1.5 kg ha^{-1} yr^{-1} wet deposition to lakes in Rocky Mountain National Park (Baron 2006). In this study, we have expanded critical loads determination across parks of the west to more broadly define a threshold for these alpine lake ecosystems. Using a similar approach to Baron (2006), we defined the critical N load as the threshold that elicits key diatom shifts, as determined by changes in lake sediment cores and reconstructed by relating the timing of diatom shifts to the inferred N deposition rate at the time. Sediment cores from the eastern Sierras, Glacier National Park (GNP), and the Greater Yellowstone Ecosystem (GYE) were used in this analysis. We used total wet inorganic N deposition data from the National Atmospheric Deposition Program (NADP), with modifications in the GYE to account for elevation. Our analyses revealed a critical N load of 1.4 kg N ha^{-1} yr^{-1} in wet deposition for the east Sierras and for the GYE. Although the GNP region exceeds this value, indicator taxa of N enrichment were only present in very low numbers in lakes of this park. Water chemistry data revealed that, unlike the Sierra and GYE lakes, GNP lakes are phosphorus limited, hence we would not expect to observe N enrichment effects in these lakes. The results of this study are in close agreement with those of Baron (2006) and expand the geographic regions over which resource managers now have a target value needed to improve aquatic ecosystem conditions.

BACKGROUND

Diatoms are a class of microscopic algae that are sensitive to environmental changes and that have cell walls which are frequently well preserved in fossil deposits in lacustrine sediments. Shifts in diatom composition are frequently the first indication of ecological perturbations. Sedimentary diatom profiles have been used in the reconstruction of limnological parameters such as pH (Charles and Whitehead, 1986; Renberg, 1990; Anderson and Renberg, 1992; Battarbee et al., 1999) and phosphorus (Anderson et al., 1990; Anderson and Rippey, 1994; Hall and Smol, 1996).

Of the major disturbances affecting alpine lakes, enhanced atmospheric nitrogen (N) deposition is one of the primary concerns, as human alteration of the global N cycle has doubled the amount of fixed N transferred from the atmosphere to land-based ecosystems (Vitousek et al., 1997). Because of atmospheric transport, anthropogenic N can affect systems far removed from the source of emission, as indicated by increased NO_3^- concentrations in the Greenland ice sheet (Mayewski et al., 1990). Although the increased quantity of fixed N in the atmosphere is now well documented, the critical N load that elicits ecological change in western alpine lakes has only recently been defined in limited areas. Baron (2006) defined a critical N load of 1.5 kg ha^{-1} yr^{-1} wet deposition to lakes in Rocky Mountain National Park. This was based on changes in sedimentary diatom profiles from that area. Specifically, increases in the two diatom taxa, *Asterionella formosa* and *Fragilaria crotonensis*, are used as indicators of N enrichment in N-limited lakes, as Saros et al. (2005) demonstrated that these two species respond positively to N enrichment in alpine lakes.

OBJECTIVES

The objective of this study was to determine a critical N load across several regions of the west using sedimentary diatom profiles. Using data collected by the NADP, we identified three additional national park areas located along a gradient of N deposition loads to include in this study. These included the eastern Sierras near SEKI, the GYE, and GNP. Sedimentary diatom profiles from two lakes from each of these parks (Table 1) were determined and used to reconstruct the timing of shifts driven by enhanced N deposition.

Table 1. Lakes in or near three national parks included in this study.

National Park	Lake	Location	Collected by:	NADP site used:
Yellowstone	Island	44°56'53.74"N 109°32'28.19"W	Saros	WY08
	Heart	44°58'59.52"N 109°32'17.62"W	Saros	
Glacier	Oldman	48°30'44.21"N 113°27'42.81"W	Landers	MT05
	Snyder	48°37'35.87"N 113°48'12.72"W	Landers	
Sequoia	Cottonwood*	36°30'09.72"N 118°13'35.12"W	Saros	CA75
	Ruby*	37°24'56.51"N 118°46'13.30"W	Saros	

*these lakes were selected based on data in the Diatom Paleolimnology Data Cooperative

The original sites selected for this study included the Northern Cascades as well. Through conversations with Linda Brubaker and Mark Abbott, it became clear that high-resolution cores from the last century were not available.

METHODS

Sediment cores were collected using gravity corers. The chronology of sediments was based on ^{210}Pb distillation and alpha spectrometry methods (modified from Eakins and Morrison, 1978), and dates and sedimentation rates determined according to the constant flux:constant sedimentation rate (CF:CSR) model (Oldfield and Appleby, 1984).

Diatom slides were prepared from digested (30% H_2O_2) sediment samples. The processed samples were settled onto coverslips and mounted onto slides with Naphrax®. A minimum of 300 valves per slide was counted under oil immersion on a Nikon E600 Eclipse microscope with differential interference contrast under oil-immersion at 600X magnification. Diatom taxonomy was based primarily on Krammer and Lange-Bertalot (1986-1991) and Camburn and Charles (2000).

We relied on changes in the two key diatom taxa, *Asterionella formosa* and *Fragilaria crotonensis*, as markers of enhanced N deposition in western alpine lakes (Wolfe et al. 2001; Saros et al. 2003; Saros et al. 2005). Hence, the timing of increases in the relative abundances of these two taxa was used as an indicator of the year in which N deposition rates first exceeded a critical load. Building off of the approach to determine critical N loads outlined by Baron (2006), the timing of these diatom shifts at each study site was compared to inferred N deposition rates for that area. For each site, we fit an exponential equation to the total inorganic N deposition data from 1980 to 2007 (i.e., the total period of record) from the nearest NADP site (Table 1).

For the Sierras, we inferred N deposition rates for the period of time during which the indicator diatom taxa first increased. The cores were collected from the east side of the range, but NADP site CA75 is located on the west side. In a comparison of trends in wet N deposition at sites on both the west and east sides of the Sierras, Melack et al. (1998) concluded that patterns are similar, hence we used the NADP data from site CA75 for this analysis.

For the GYE, to account for deposition differences due to elevation, we compared average total wet inorganic N deposition data from NADP site WY08 from 1993-2006 to calculated average annual wet nitrate deposition values (Nanus et al. 2003) for the locations of the cored lakes. We calculated a ratio of deposition at the core sites to that at the NADP site, and multiplied the NADP data from 1980-2007 by this ratio. An exponential equation was fit to these adjusted data, and, to determine a critical load, the equation was solved for the first year in which the indicator diatom taxa increased in the sediment cores.

RESULTS

Diatom profiles were determined for six lakes across the three study areas (Figs 1-6), with the N-enrichment indicator taxa indicated in red across all figures. In the Sierras, *A. formosa* increased in relative abundance starting between 1960-1965 across the two study lakes (Figs. 1, 2). The remainder of the diatom assemblages were dominated by typical alpine taxa routinely found in dilute, nutrient-poor waters; their relative abundances declined as that of *A. formosa* increased. In the GYE, the increases in *A. formosa* occurred after 1980 (Figs. 3, 4), again with the relative abundances of typical alpine taxa declining. The shift in diatom taxa in the GYE is accompanied by a decline in the sedimentary $\delta^{15}N$ values, suggesting an increase in loading of recently fixed N to these systems rather than changes in trophic structure (i.e., fish stocking, which would lead to heavier $\delta^{15}N$ values). The timing of the initiation of fish stocking programs in this area (1930's) does not coincide with any changes in sedimentary diatom taxa. In GNP, although the N indicator taxon *F. crotonensis* is present, it did not increase in either of the two lakes over the last century (Figs. 5, 6).

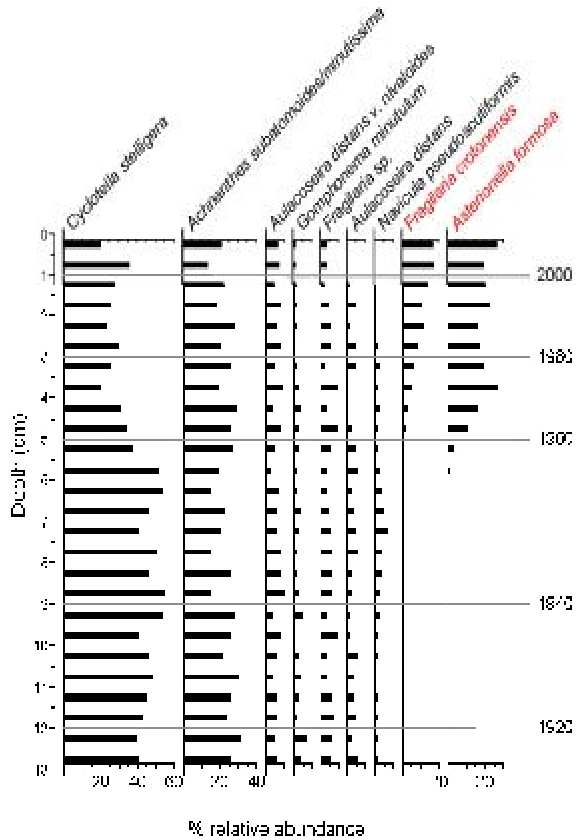

Figure 1. Sedimentary diatom profile from Ruby Lake (East Sierras). Dates from ^{210}Pb analysis indicated on the right.

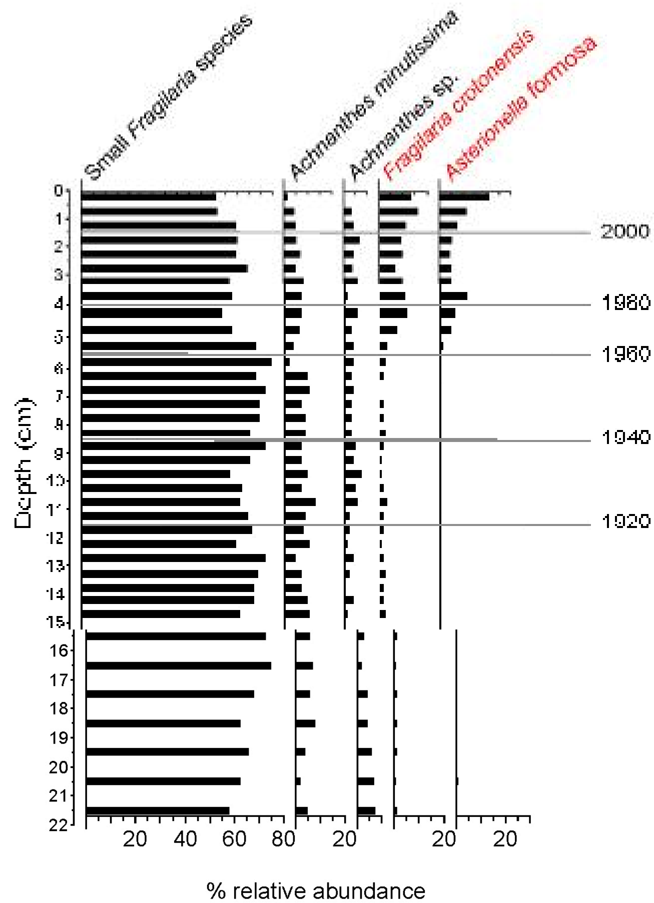

Figure 2. Sedimentary diatom profile from Cottonwood #5 Lake (East Sierras). Dates from ^{210}Pb analysis indicated on the right.

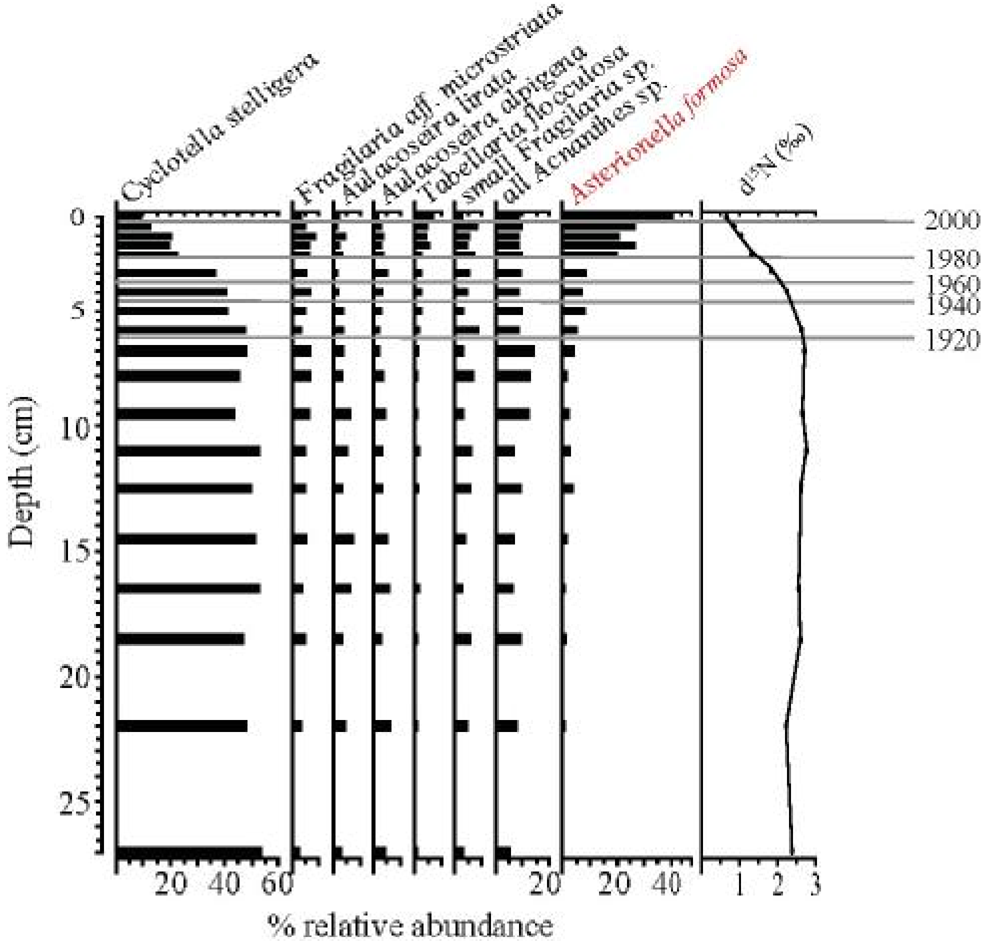

Figure 3. Sedimentary diatom profile from Island Lake (Greater Yellowstone Ecosystem). Dates from ^{210}Pb analysis indicated on the right; these cores were also analyzed for del^{15}N.

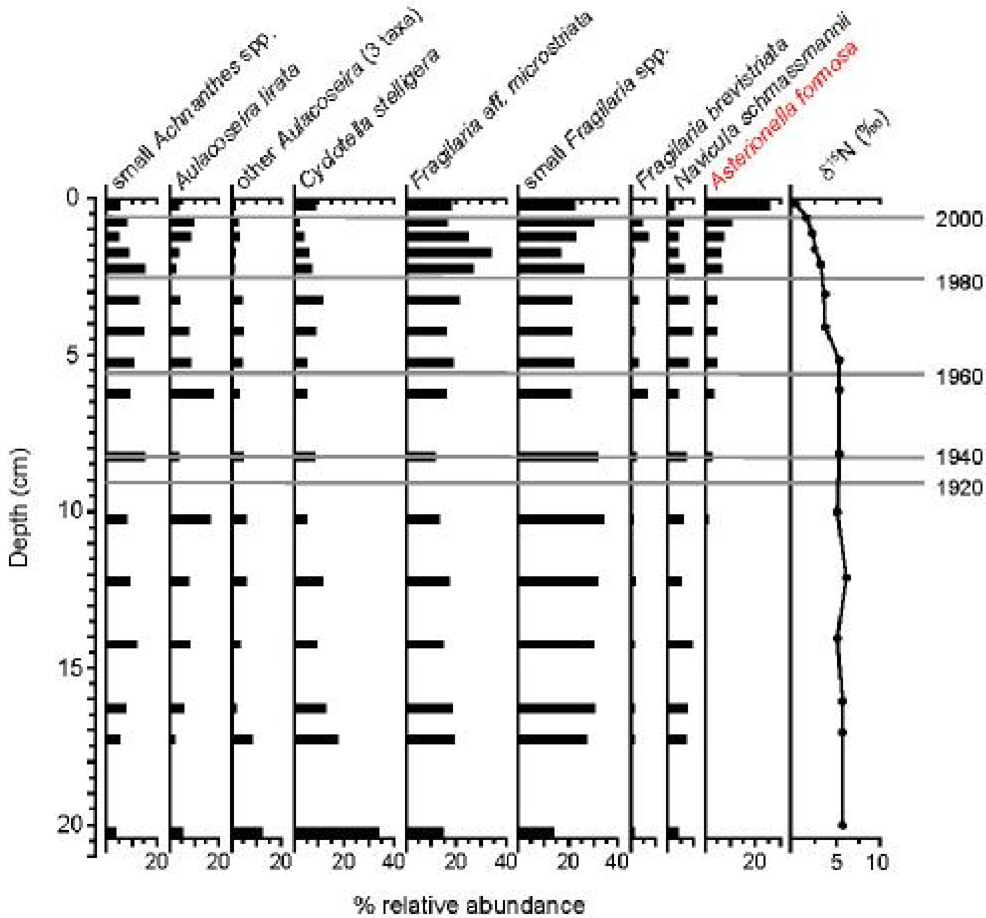

Figure 4. Sedimentary diatom profile from Heart Lake (Greater Yellowstone Ecosystem). Dates from ^{210}Pb analysis indicated on the right; these cores were also analyzed for del^{15}N.

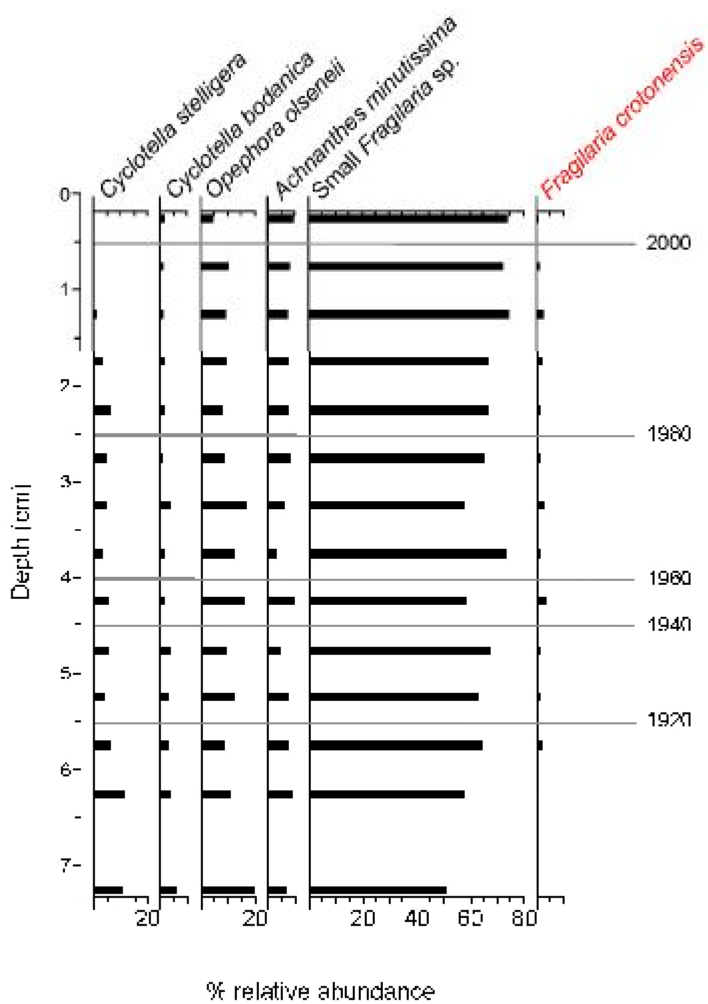

Figure 5. Sedimentary diatom profile from Oldman Lake (Glacier National Park). Dates from ^{210}Pb analysis indicated on the right.

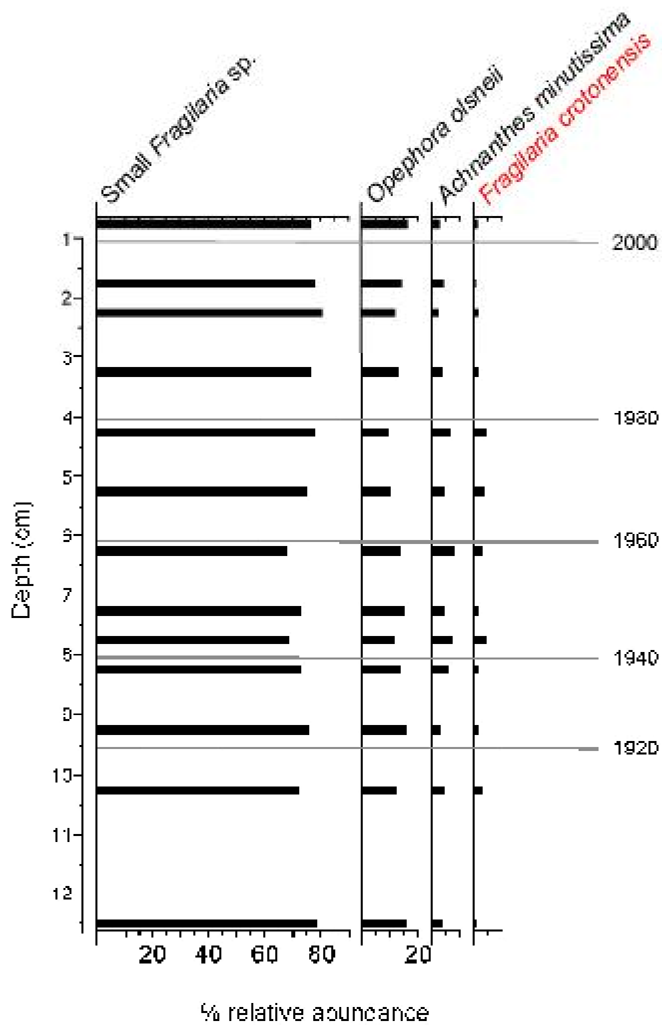

Figure 6. Sedimentary diatom profile from Synder Lake (Glacier National Park). Dates from ^{210}Pb analysis indicated on the right.

East Sierras
For the NADP site CA75, the exponential equation of year compared to total wet inorganic N deposition was:

$$y = (2 \times 10^{-15})\, e^{0.0174x}$$

where x = year and y = total wet inorganic N deposition ($R^2 = 0.105$; Figure 7). Solving for each year between 1960-1965, an average N deposition value of 1.4 kg ha^{-1} yr^{-1} was obtained for that period.

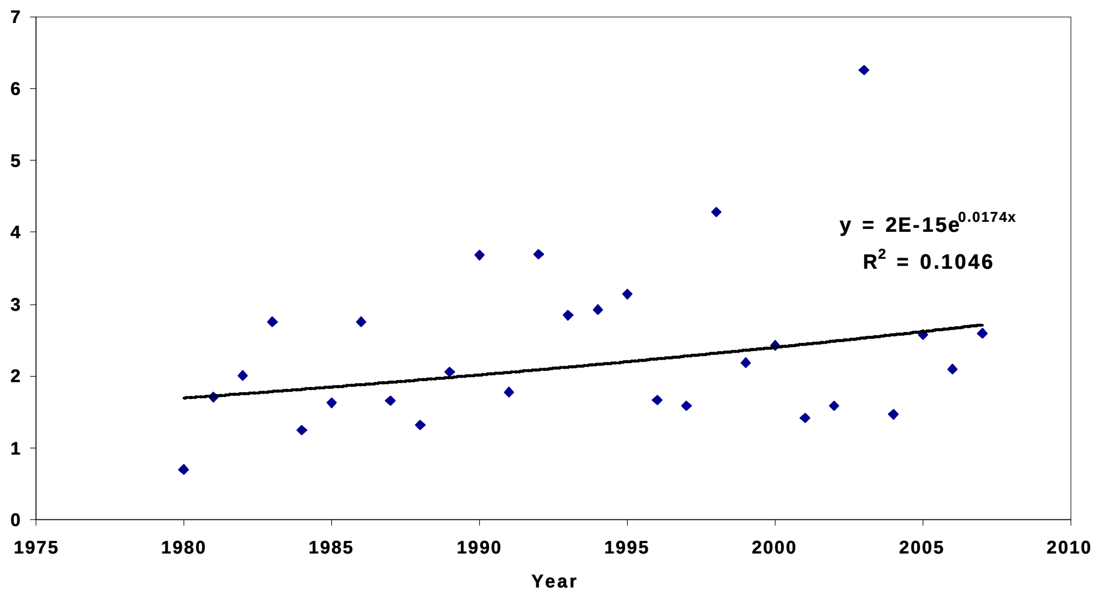

Figure 7. Exponential fit to the NADP data from CA75 between 1980-2007.

Greater Yellowstone Ecosystem
Diatom changes in this area occurred around 1980, which was the first year of measurement at the nearest NADP site. Average wet nitrate deposition values from 1993-2006, calculated from the approach of Nanus et al. (2003) for the coordinates of the cored lakes, was 1.8 kg ha^{-1} yr^{-1}, while average total wet inorganic N deposition for the same period from the NADP site was 1.0 kg ha^{-1} yr^{-1}. We adjusted NADP data using the ratio of 1.8/1.0, and the resulting exponential equation for adjusted data from 1980-2007 was:

$$y = (1 \times 10^{-10})\, e^{0.0118x}$$

where x = year and y = total nitrate deposition ($R^2 = 0.158$). Solving for 1980, when diatom changes increased in the two cored lakes, results in a critical load of 1.4 kg N ha^{-1} yr^{-1} wet deposition.

Glacier National Park
The N-enrichment indicator taxon ***F. crotonensis*** was present in both GNP lakes but never increased in the sediment records of these lakes. These two lakes, Oldman and Snyder, are part of the WACAP study. Water quality data from this study indicate that DIN:TP values for these lakes are 18.2 and 11.2, respectively, suggesting that these lakes, like many in the GNP area, are phosphorus limited.

CONCLUSIONS
Analyses of sedimentary diatom profiles from lakes in the eastern Sierras and Greater Yellowstone Ecosystem yielded the same critical N load value of 1.4 kg N ha^{-1} yr^{-1} wet deposition for eutrophication effects of this deposition. In contrast, the two lakes of Glacier National Park appeared undisturbed by N deposition to that area. The calculated values are in close agreement with that determined by Baron (2006) using similar methods for Rocky Mountain National Park, and expand the geographic range over which critical loads have been quantified.

BUDGET
All of the funds allocated to this project ($10,088) have been spent. In addition, the University of Maine provided funding for the unanticipated travel to the Sierras to collect new cores from that area.

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