Dust mediated transfer of phosphorus to alpine lake ecosystems of the Wind River Range, Wyoming, USA

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Abstract

Alpine lakes receive a large fraction of their nutrients from atmospheric sources and are consequently sensitive to variations in both the amount and chemistry of atmospheric deposition. In this study we explored the spatial changes in lake water chemistry and biology along a gradient of dust deposition in the Wind River Range, Wyoming. Regional differences were explored using the variation in bulk deposition, lake water, sediment, and bedrock geochemistry and catchment characteristics. Dust deposition rates in the Southwestern region averaged 3.34 g m^{-2} yr^{-1}, approximately 3 times higher than deposition rates in the Northwestern region (average 1.06 g m^{-2} yr^{-1}). Dust-P deposition rates ranged from 87 μg P m^2 day^{-1} in the Northwestern Region to 276 μg P m^2 day^{-1} in the Southwestern region. Subalpine and alpine lakes in the Southwestern region had greater total phosphorus (TP) concentrations (5-13 μg L^{-1}) and greater sediment phosphorus (SP) concentrations (2- 5 mg g^{-1}) than similar lakes elsewhere in the region (1-8 μg L^{-1} TP ,0.5-2 mg g^{-1} SP). Lake phosphorus concentrations were related to dissolved organic carbon (DOC) across vegetation gradients, but related to the percent of bare rock, catchment area to lake area, and catchment steepness across dust deposition gradients. Modern phytoplankton and zooplankton biomasses were 2 orders of magnitude greater in the Southwest than in the Northwest, and alpine lakes in the Southwest had a unique diatom species assemblage with relatively higher concentrations of *Asterionella formosa, Pseudostaurosira pseudoconstruens,* and *Pseudostaurosira brevistriata*. These results suggests that catchment controls on P export to lakes (i.e.DOC) are overridden in dominantly bare rock basins where poor soils cannot effectively retain dust deposited P.

Key words: Atmospheric Deposition; Dust; Phosphorus; Alpine Lakes; Wyoming

Introduction

Climate and human factors have accelerated the rate of erosion, and hence dust generation in many semi-arid and arid regions around the world; On a global scale, dust records suggest that emissions have roughly doubled over the last century (Mahowald 2010). In the US, an estimated 1Tg of dust is deposited per year (Tanaka and Chiba 2006). Though there are no continuous long-term records of dust deposition in the western US, proxy evidence suggests that dust deposition has increased 2-5 times from the 19th to the 20th century (Neff et al. 2008) and by up to 400% in the last two decades in many western areas (Brahney et al. 2013) .

Dust is an important agent of nutrient delivery to freshwater ecosystems. The wind erosion of soil preferentially removes fine-grained silt and clay material relative to the coarse-grained sand material (Pye and Krinsley 1986). Rock-derived nutrients, including the base cations and phosphorus (P), tend to be most concentrated in the soil fine fraction that is prone to loss during erosion (Caravaca et al. 1999; Li et al. 2009). As a result, the erosion of semi-arid soils has the potential to be an important flux of nutrients to downwind ecosystems. Phosphorus in dust is on average enriched by 1.6 times that of the upper continental crust (Lawrence and Neff 2009). Since P is a common limiting nutrient in lake ecosystems, increased deposition has the potential to alter the nutrient limitation regime (Sickman et al. 2003; Camarero and Catalán 2012), stimulate primary productivity, shift bacterial abundance and phytoplankton species composition (Pulido-Villena et al. 2008; Morales-Baquero et al. 2006). Dust may also contribute base-cations and acid-neutralizing carbonate minerals as dust aerosols are often sourced from sedimentary rock types. In Europe, dust from the Sahara has been shown to contribute acid-neutralizing capacity (ANC) to lakes in crystalline basins that receive acid deposition (Rogora et al. 2004).

Alpine lakes typically have small catchments with limited soil and vegetation cover. These lakes may be particularly sensitive to variation in the amount and chemistry of atmospheric deposition because nutrient fluxes from the atmosphere can represent a large fraction of the catchment nutrient budget, see for example Kopáček (2011). Here we use a gradient in dust deposition across lakes in the Wind River Range (WRR) of Wyoming to evaluate the impacts of dust deposition on alpine ecosystems. The WRR is an ideal site for evaluating the effects of dust deposition on alpine lake ecosystems for several reasons. First, the geography of the region allows for a natural division between dust impacted and non-dust impacted lakes. The local dust source in the Green River Valley is situated to the Southwest of the range (Dahms 1993; Dahms and Rawlins 1996) (Figure 1). Previous work has shown that a gradient in dust deposition across the range exists, with dust deposition diminishing with distance from the Green River Valley source (Dahms 1993). Second, it is possible to control for other variables that may influence alpine lake biogeochemistry including geology, catchment vegetation, climate, and nitrogen deposition.

The objectives of this study were to 1) characterize spatial variation in total dust deposition across the WRR, 2) evaluate the potential influence of dust deposition on alpine lake water chemistry, and 3) determine if dust-mediated shifts in lake water chemistry are sufficient to alter plankton species composition and biomass. We hypothesized that the southwestern area of the WRR receives more dust than other regions, and that lake nutrient concentrations would vary across gradients of dust deposition and catchment characteristics.

Methods

Study sites

The WRR is located in west central Wyoming bounded by the semi-arid Green River Basin to the southwest and the Wind River Basin to the east. The WRR has a relatively uniform geology that is mainly composed of Achaean granites (Koesterer et al. 1987) (Figure 1). To the south and west of the range are large areas of sagebrush scrubland underlain by the Green River

Formation, which has a distinctly different geology than the WRR. The Green River Formation is composed of sandstone, siltstones, limestones, evaporates, and volcanic ash layers (Sullivan 1980). The predominant wind direction is westerly and southwesterly throughout the year and winds are strongest through the winter months (Dahms and Rawlins 1996)(Figure 1).

In the study areas the subalpine forest of mixed conifer ranges from 2900-3100 masl, with scattered tree stands up to 3200 masl (Dahms 1993). Alpine tundra vegetation or bare rock exists above 3100 masl. In general the subalpine region has varying thickness of sandy ground moraine and alpine soils are thin and stony if present (Dahms 1993). The alpine region in the southwest and southeastern areas and characterized by large tors, i.e. smooth convex rock outcrops with little regolith formation. The alpine regions in the northern areas have lower relief rock outcrops that are thinly mantled with regolith.

There are no high elevation climate stations in the range, the stations nearest to the western slope include Boulder (42.72, -109.69) at 2115 masl and Pinedale (42.88.-109.86) at 2193 masl, and Big Piney (42.58,-110.11) in the Green River Valley at 2125 masl. Based on 1981-2010 Climate Normals, annual average precipitation is 1140 mm at Pinedale, 972 mm at Boulder, and 648 mm at Big Piney. Average annual temperatures are similar for all sites at 2-3°C (NOAA 2014).

Dahms (1993) measured the aeolian contribution to soils along three transects in the WRR, defined as ‘southern’, ‘mid-range’, and ‘northern’. Along each transect, soils were sampled at 10, 20, and 30 km from the Green River Basin. The transects began in the piedmont on the western slope and travelled upslope ending in the western alpine zone. Dahms (1993) used the presence of volcanic minerals (hornblende, zircon, apatite) present in the Green River Basin but not found in the prevailing geology of the WRR to distinguish between aeolian and local contributions. The highest fractional contribution of Green River Basin volcanic minerals to soils were found in the ‘southern’ transect, closest to the Green River Basin, with the ‘mid-range’ following in abundance, and the ‘northern’ region having the lowest concentrations. The average deposition rate measured over a two-year period for the ‘southern’ area was 5.1 g m^{-2} yr^{-1} (Dahms and Rawlins 1996). Though wind speeds are greatest through the winter months, dust deposition was found to be highest from July to September due to dry, snow-free conditions in the Green River Basin (Dahms and Rawlins 1996).

Our analysis was primarily concerned with the potential effects of dust deposition on lake chemistry and biology in the WRR. Though there are over 1300 lakes in the WRR, access to alpine and subalpine regions in northern and eastern regions is limited by rough and inaccessible terrain. Therefore, for some analyses, we expanded our dataset by including data from subalpine and alpine lakes from the nearby Teton Range. The Teton Range is located to the northwest of the WRR (Figure 1) and the underlying geology is predominately granite, gneiss, and schist (Love 1968). The alpine regions in the Teton Rage are characterized by thin soil formation and steep rocky catchment slopes.

Sampling strategy

Based on the results of Dahms and Rawlins (1996), we hypothesized that the southwestern region of the WRR would receive more dust than the other regions due to the proximity of this region to the Green River Basin and to the dominant wind direction. We then selected four regions of the WRR to cover a gradient of expected dust deposition rates. Because the WRR is a designated wilderness area and motorized vehicles are not permitted, sampling areas were chosen based on foot access to multiple lakes located within 10-15 miles from their respective trailheads. Sampling areas can be found in Figure 1, in the WRR these are, the Southwest, West-Central, Northwest, and Southeast. The Southwest, West-Central, and Northwest correspond to the ‘southern’, ‘mid-range’, and ‘northern’ transects respectively used in Dahms (1993). Lakes from the Teton Range are from the eastern slope.

To determine dust deposition rates and dust geochemistry we set up bulk deposition samplers in three locations on the western slope of the range. These are Southwest, West-Central, and Northwest. Due to access difficulties, we were unable to maintain deposition samplers in the Southeast slope.

To evaluate spatial differences in lake chemistry, and to relate these differences to either variation in local catchment properties or to atmospheric deposition, we sampled from the deepest section of each lake, 1) water from the upper meter of the lake, and 2) the top one cm of the lake sediments. We also sampled catchment bedrock in all Wind River regions. Our chemical analyses focused on elements that are of high concentration in atmospheric deposition (Reynolds et al. 2010; Marx et al. 2005; Lawrence and Neff 2009), specifically P, Ca, Cd, Cu, Sb and Pb. We were particularly interested in the deposition of P because it is biologically relevant and compositional dust measurements conducted by Dahms (1993) indicate high organic content and the presence of apatite, a P-rich mineral commonly associated with mineral dust. Both organic material and apatite have the potential to contribute P to downwind ecosystems. Calcium is a useful indicator of atmospheric dust concentrations as it is primarily derived from mineral sources in this portion of the country (Meszaros 1966; Sequiera 1982). Lastly, a number of heavy metals including Cd, Cu, Sb, and Pb are emitted during upwind mining and industrial processes and can become concentrated on dust particles (Morselli et al. 2003; Marx et al. 2005; Lawrence and Neff 2009; Brahney et al. 2013). These elements have also been identified as a common component of dust deposition in nearby mountain ranges (Reynolds et al. 2010; Lawrence et al. 2010).

To evaluate the effects of lake chemistry on diatom populations we employed two different strategies. One, we used statistical analysis to examine the relation between lake water chemistry and surface sediment diatom community composition. We restricted our analysis to alpine and subalpine lakes because we hypothesized that the biogeochemical effects may be more apparent in these catchment types. In addition, we wished to sample across the dust deposition gradient, using alpine and subalpine lakes removes the confounding factors in species composition that may arise from vegetation-type gradients e.g. shallow grassland piedmont lakes to alpine lakes. In the WRR, subalpine and alpine lakes are only present in the Southwest, Northwest, and Southeast. To increase our lake and diatom sample set, we included data from a study with a similar sampling design conducted in the nearby Teton Range (S. Spaulding unpublished data). Two, we sampled live phytoplankton and zooplankton from 2 areas in the WRR. We chose the Southwestern region and the Northwestern region as *a priori* end-members representing high- and low-dust regions respectively.

Atmospheric Sampling

We used bulk deposition collectors to estimate the non-soluble dry fraction. Samplers were placed in triplicate at several locations over the 2009 and 2010 ice-free season. In 2009, samplers were installed in the Southwestern region at Black Joe Lake and in the Northwestern region in the Seven Lakes area. In 2010, samplers were placed in the Southwestern region at Black Joe Lake and in the West-Central region at Hobbs Lake. As noted above, we were unable to maintain a bulk sampler on the eastern slope of the range due to site access difficulties.

Bulk deposition samplers were composed of polyethylene funnels that were 16 cm in diameter and filled with glass marbles to effectively capture dry deposition. The funnels were mounted on posts 2 m above ground. The base of the funnel was fitted with Tygon tubing allowing the sample to drain in to opaque brown Nalgene bottles. The funnels were fitted with a 'bird-ring' consisting of an insulated metal ring fastened to the base of the collector funnel. The bird-ring was twice the diameter of the funnel and encouraged birds to sit on the ring rather than the sampler, minimizing the potential for fecal contamination (Dämmgen et al. 2005). A small piece of nylon mesh was fitted in the drain to prevent contaminants from entering the bottle. The sample bottles were exchanged every 1-4 weeks after rinsing the apparatus with 50 mL of DI water and kept frozen until transport to the University of Colorado.

In 2009, the non-soluble dry deposition was separated from wet deposition by filtration through pre-weighed Whatman #42 filter papers. Dust deposition rates for 2009 were based on these filter weights for the sampling periods. Due to low sample weights for each period, we were unable to collect enough material for geochemical analysis. To solve this problem, in 2010, sampling frequency was reduced and multiple samples were pooled and evaporated to retain enough dry material for weighing and geochemical analysis. Salts that precipitated during the drying process were removed through sediment washing, aspirating, and re-drying. At the Southwestern sampling area, 3 samplers were pooled from 06/27/2010 to 08/16/2010, and 3 from 08/16/2010 to 09/04/2010. At the Western region, all 3 samplers were pooled from 06/29/2010 to 09/03/2010. A small fraction of each dry sample was retained for geochemical analysis and the remainder pooled and used for $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotopic analysis (described below). Analysis of major and minor element concentration on dry dust samples were conducted at the Laboratory for Environmental and Geological Studies (LEGS) at the University of Colorado after digestion via trace element grade HCl, HNO_3 and HF, and H_2O_2 (EPA 1996). Samples were analyzed using a Perkin Elmer Elan DRC-E ICP-MS and an ARL 3410+ ICP-AES.

Atmospheric samplers in the Southwest region were co-located with the US Forest Service long-term atmospheric deposition and lake monitoring site at Black Joe Lake (Grenon 2010).

The USFS has maintained a continuous sampling program of bulk snow, rain, and lake water chemistry since 1984 at Black Joe Lake (Southwestern region) and data is available from 1995 to present. The USFS does not sample deposition chemistry for TP concentrations; however, they do sample other elements that may be indicative of deposition chemistry including acid-neutralizing capacity (ANC), Ca^{2+}, NH_4^+, NO_2^-, NO_3^{2-}, SO_4^{2-} and pH. Forest service deposition data is collected throughout the year at 2-5 week intervals, following USFS sampling protocols (USDA/FS 2002; Grenon 2010). Briefly, rain is collected in a modified Hubbard-Brook rain collector in the summer, and using a snow tube 18" in diameter in the winter. Samples are collected every 2 weeks in the summer and every 3-5 weeks in the winter (Grenon 2010). Due to differences in analytical methods, we do not attempt to integrate our data set with the USFS data; however, because the USFS also collects lake water chemistry data (see below) this affords us a unique opportunity to examine the temporal changes in deposition and lake water chemistry using regression analysis.

Lake water chemistry

We sampled water from 32 lakes in the four regions of the WRR in 2009 and 2010 and from six lakes in the Teton Range in 2010. In the Wind River lakes, water samples were taken in June after ice-off and prior to stratification in an attempt to capture maximum annual nutrient concentrations. Integrated water samples from the upper meter of the lake were taken from the pelagic region using a 1m long polyethylene tube and filtered through a 100 μm Nitex® mesh to remove zooplankton biomass. From this, at least 400 ml were passed through a pre-combuste 0.7 μm Whatman® GF/F filter for particulate carbon and nitrogen analysis, at least 400 ml were filtered through a 0.45 μm Millipore® Nylon membrane for particulate geochemistry and 100 ml was kept for ANC, pH, and DOC analysis in brown Nalgene® bottles, 100 ml were acidified and kept in a brown Nalgene bottle for nutrient analysis. *In situ* measurements of temperature and pH were taken using a YSI 6600 V2 Sonde. In the Teton Range, water was sampled at a central location of each basin from an inflatable raft using a Van Dorn sampler and transferred to shore in an acid washed carboy. A portion of the sample was filtered through a pre-rinsed, pre-combusted 47-mm, Whatman® GF/F for filtrate collection. From this, 100 mL of filtered sample was kept for immediate analysis of NH_4^+ and later analysis of anions and cations, 75 mL of unfiltered sample was kept for pH, conductivity, ANC and total phosphorus. A pre-combusted glass amber bottle with Teflon lid was used for collection of dissolved organic carbon (DOC), total nitrogen and total dissolved nitrogen. Samples from both regions were collected in Nalgene® high density polyethylene (HDPE) bottles and kept cold in nearby rivers during sampling expeditions, transported on ice in coolers, and delivered refrigerated or frozen to the Kiowa Environmental Chemistry Lab.

All water samples from both regions were measured for cations, anions, TP, DOC, DIN, and total nitrogen (TN). Cations were measured with a flame atomic absorption spectrometer, Perkin Elmer Analyst 200; ammonium (Detection Limit (DL) 0.50 μeq L^{-1}) with a fluorescence detection plate reader, BioTeck Synergy^{TM} 2; nitrate (DL 0.03 μeq L^{-1}) with an automated chemical analyzer using continuous flow analyses, OI Analytical Flow Solution® IV; anions with ion chromatography using a Metrohm 761 Compact IC. TN (DL 0.98 μeq L^{-1}) was run on a Shimadzu TOC-V-CPN Total Organic Carbon Analyzer. Samples for TP were digested and oxidized with potassium persulfate and 3.75N NaOH. TP (DL 0.04 μeq L^{-1}) and nitrate (0.06 μeq L^{-1}) was run on a Lachat QC 8500 Spectrophotometric Flame Injection Analyzer. DIN is the sum of NO_3^- and NH_4^+. Acid-neutralizing capacity is measured by gran titration, and DOC was measured using a filtered sample on a Shimzadzu TOC-V-CPN Total Organic Carbon Analyzer. All methods for the Kiowa Lab can be found online (LTER 2013)

The USFS collects 2-5 water samples during the ice-free period from the inlet and outlet streams, as well as the epilimnion and hypolimnion of Black Joe Lake, Southwestern Region

(USFS *personal communication*). Samples are analyzed at the joint USFS and USGS Air Program Laboratory in Fort Collins, Colorado. Because USFS data for both atmospheric deposition and lake chemistry spans several decades, we compared the historical deposition of Ca^{2+}, ANC, and TN in the Blake Joe Area to historical lake water concentrations in Black Joe Lake.

Sediment Chemistry

In both the WRR and the Teton Range a Sound Navigation and Ranging (SONAR) instrument was used to determine the deepest point of each lake. Sediments were collected from the top one cm of all 32 lakes. In the Wind River lakes, an Ekman box-corer fitted with a polycarbonate insert was used to sample sediments. In the Tetons, sediments from 6 lakes were collected using a modified Kajak-Brinkhurst coring device (Glew, 1989) fitted with a clear polycarbonate core tube. Cores were extruded on site and bagged in labeled Whirl-Pak bags and kept cool until return to the University of Colorado. In addition, representative bedrock samples were taken form 15 catchments around the WRR to evaluate regional differences in geochemistry.

All sediment and bedrock samples were measured for major and minor elements. Sediment samples were weighed and freeze-dried. The weathering rind was removed from the bedrock samples prior to grinding to remove artifacts related to the preferential weathering of certain elements. Sediments were digested using trace element grade HCl, HNO_3, and HF, and H_2O_2 as per EPA guidelines (EPA 1996). Elements for bedrock samples were run on an ELAN DRC-e Quadrupole ICP-MS at the US Geological Survey in Denver, CO. Major and minor elements for sediment samples were measured at the LEGS at the University of Colorado. Untreated sediments were analyzed for organic carbon and nitrogen on a Costech ECS 4010 Analyzer at the University of Colorado. All sediment samples were calibrated against NIST standards.

Because the source region, the Green River Basin, and the depositional regions in the WRR have bedrock geologies of different composition and age, we could use isotopic measurements of ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr to separate the provenance of sedimentary material within a lake basin (Grousset and Biscaye 2005). We used the dust samples collected in 2010 and a bedrock sample for the North Lake basin as end-members. We used samples form the sediment core depths of 0.25-0.5 cm and 0.5-0.75 cm from North Lake, Southwestern region to determine dust concentration in the sediment. North Lake has no geographic barrier to the major dust sources upwind and is the site most geographically predisposed to dust deposition in the Southwestern region. The concentration of dust within the surface sediments of North Lake was calculated using a constrained least-squares regression analysis. Constraints were such that the proportion of bedrock and dust must each have a concentration between 0 and 1, and the sum of the bedrock and dust proportions must equal 1. The unweighted Euclidean distance metric was used to determine the minimum error. The flux of dust to the lake sediment floor was estimated by multiplying the dust fraction by the sedimentation rate at each interval. Sedimentation rates were calculated from ^{210}Pb dated cores in North Lake (Brahney 2013). Based on these rates we expect the surface sediments (0-0.75cm) to integrate 5-10 years of data. Note that this flux represents the focusing of dust from the catchment to the lake sediment floor and not the estimated flux of dust from the atmosphere; we term this measurement the ‘catchment integrated flux’.

Neodymium and strontium isotope analysis were completed at the Thermal Ionization Mass Spectrometry Lab at the University of Colorado in Boulder using a Finnigan-MAT 6-collector solid source mass spectrometer. The dust and lake sediments were initially ashed and leached with HCL to remove organic matter and other labile mineral fractions. Digestion of all samples for isotope analysis followed the methods outlined in Pin et al. (1994).

Diatom preparation and analysis

Surface sediment samples collected as described above from 32 lakes in the Wind River and Teton Ranges were prepared for diatom analysis. Surface sediments were prepared using 5 mg of dry sediment digested in 30% hydrogen peroxide solution and placed in a hot water bath for 2 days. Sediments were rinsed with de-ionized water and centrifuged, repeating until the solution measured neutral pH (Battarbee et al., 2001). Diatom slurries were pipetted onto glass cover slips, dried overnight and mounted using Zrax mounting medium. Alternate sediment sections were chosen for enumeration with a minimum of 300 diatoms counted in the Teton Range and 500 in the WRR. Diatoms were counted using Olympus BX51 and Vanox microscopes equipped with differential interference contrast optics and a 1.3 NA 100X oil-immersion objective. Diatom species identifications were based on taxonomic literature that included several volumes (Krammer & Lange-Bertalot, 1985, 1986, 1991; Krammer & Lange-Bertalot, 1988, 2000; Patrick & Reimer, 1966).

Plankton species composition

An additional liter of water was sampled from the upper meter of five lakes in the WRR and preserved with Lugol's solution. The five lakes were selected from different elevations, three from the Southwest and two from the Northwest to contrast high and low dust regions. From the Southwestern region we analyzed North Lake (alpine), Black Joe Lake (alpine), and Meeks Lake (forest/grassland mix), and from the Northwestern region we analyzed Divide Lake (alpine) and Twin Lake South (forest/grassland mix). Phytoplankton and zooplankton species were counted for these samples at BSA Environmental Services, Beachwood, Ohio. Plankton organisms were identified to the species level and zooplankton biomass (μg L^{-1}) and phytoplankton biovolume (μm^3 L^{-1}) were calculated.

Statistical Analysis – Spatial differences in lake water and sediment chemistry

We used Google Earth Professional to determine lake area and catchment area, as well as percent cover of forest, grass/shrub (including alpine vegetation), and bare rock. Based on these estimates and elevation criteria we divided lakes into three classes, alpine, >80% bare rock in the catchment, subalpine, 50-80% bare rock in the catchment and forest/grassland, for all remaining lakes. A distance-weighted catchment steepness index was developed by calculating the gradient in eight cardinal directions and then multiplying the gradient by the length of the catchment n each direction. The eight values were averaged to provide the catchment steepness index for each lake.

We used the non-parametric Kruskal-Wallis test to evaluate whether significant regional June (spring turnover) lake water and bulk sediment chemistry differences exist in the WRR. In each region we used only alpine and subalpine lakes to avoid confounding factors due to differences in catchment vegetation type (Southwest, n=6; Northwest, n=4; Southeast, n =3). Note there are no alpine or subalpine lakes in the West-Central region (Table 1). We chose the Kruskal-Wallis test due to small group sizes and large differences in group variance (Davis 2002). We tested for regional differences in TP, TN, TN:TP (mass ratio), SP , DOC, pH, and particulate Ca (α =0.1). We also tested sediments for common industrial heavy metals (Cd, Cu, Sb, and Pb). To evaluate post-hoc significant differences between regions, we used a non-parametric relative contrast effect test in R (α =0.1). The test uses a Tukey test with *p*-values computed from a one-tailed t-test (Konietschke et al. 2012).

We used correlation analysis to evaluate effects of catchment properties on SP and lake TP. Catchment properties include, bedrock P, altitude, lake area, catchment area, catchment area to lake area ratio (CA:LA), and the percent of forest, grass/shrub, or bare rock in each catchment. We specifically used bedrock P and vegetation type and amount compared to both SP and TP to evaluate the null hypothesis that lake P is related to vegetation characteristics and bedrock P concentrations. The alternative hypothesis is that TP and SP are controlled by external sources.

Statistical Analysis – Lake Chemistry on Species Composition

We relate the variation in diatom species assemblages to environmental variables (watershed properties as above and lake nutrient parameters) using both unconstrained and constrained ordination analysis using Canoco version 5 (Microcomputer Power, Ithaca, New York, United States). We used alpine and subalpine lakes from both the Wind River and Teton Ranges for this analysis. We used surface SP concentrations as an additional measures of between-lake phosphorus availability (Allan et al. 1980). Unlike point water samples, sediment values integrate annual or multiyear environmental characteristics. For these reasons, we included SP in the analyses. In the unconstrained ordination we defined the ordination space using species composition, and overlay the environmental variables and regional area groupings. We used Detrended Correspondence Analysis (DCA) to determine if species responses were unimodal or linear, since the gradient length was greater than 2 standard deviation units we determined the species response to be unimodal and therefore also used Canonical Correspondence Analysis (CCA).

Watershed and nutrient properties were normalized to the maximum value and were scaled to unit variance. Diatom data were expressed as the proportion of species to the total count in each sample. Diatom species were limited to those that made up more than 2% in abundance and were found in more than 5% of the lakes.

Results

Deposition rates and chemistry

Dust deposition rates were highest in the Southwest region at 9.2 mg m^{-2} day^{-1} (3.35 g m^{-2} yr^{-1} scaled-up to an annual rate for comparison to other studies), marginally higher than the West-Central region (8.2 mg m^{-2} day^{-1}, 3.00 g m^{-2} yr^{-1}) and more than 3x higher than deposition rates in the Northwestern region (2.9 mg m^{-2} day^{-1}, 1.06 g m^{-2} yr^{-1}) (Table 2). The scaled annual deposition rates are comparable to those found by Dahms and Rawlins from 1988-1990 at 5.1 g m^{-2} yr^{-1}, and the regional pattern is similar to that in Dahms (1993). These rates are low- to mid-range as compared to other alpine regions that receive dust; in the French Alps dust has been measured at 2.1 g m^{-2} yr^{-1} (DeAngelis and Gaudichet 1991), in the San Juan Mountains of Colorado, 5 g m^{-2} yr^{-1} (Lawrence et al. 2010), and in the German Alps, 49.3 g m^{-2} yr^{-1} (Kufmann 2006).

Dust geochemistry from pooled 2010 samples indicated that dust- P concentrations are on average 3 mg g^{-1} (±0.15). This is three times the average aeolian dust composition of 1.09 mg g^{-1} (±0.14) reported in a synthesis of global measurements (Lawrence and Neff 2009), though smaller than values measured in southeastern Australia at 4.3 mg g^{-1} (±1.81) (Leys and McTainsh 1999). Multiplying our dust-P concentration by the total dust deposition rates gives a dry P deposition rate of 276 μg P m^2 day^{-1} (10 mg m^{-2} yr^{-1}) over the summer season in the Southwestern region, 246 μg P m^2 day^{-1} (9 mg m^{-2} yr^{-1}) in the West-Central region, and 87 μg P m^2 day^{-1} (3 mg m^{-2} yr^{-1}) in the Northwestern region. Values in the Southwestern and West-Central region were higher than rates found in the southern Sierra Nevada Mountains of

California (7-118 μg P m^2 day^{-1}) (Vicars et al. 2010), the Tatra Mountains between Poland and Slovakia (39-78 μg P m^2 day^{-1})(Kopáček et al. 2011) and the Sierra Nevada mountains of Spain (24 -38 μg P m^2 day^{-1}) (Morales-Baquero et al. 2006), but considerably lower than the deposition rates measured in southeastern Australia at ~795 μg P m^2 day^{-1}(Leys and McTainsh 1999). Due to our sampling methods, it is possible that the dust-P concentration, and therefore deposition rates, underestimate dust-P deposition due to particle dissolution in the bulk samplers.

Spatial differences in lake water and sediment chemistry

We evaluated the mean difference in lake water sampled in June and bulk sediment chemistry for subalpine and alpine lakes between regions, focusing specifically on elements that are commonly found in atmospheric deposition. There were broad regional differences in both bulk lake sediment chemistry and water concentrations for a number of dust-related elements with a trend toward elevated concentrations of lake TP, and SP, Pb, Sb, Cu, and Cd in the Southwest region (Figure 2). The Kruskal-Wallis test found significant regional differences in SP, Ca, and Pb at $p < 0.05$ and TP at $p < 0.1$, and marginally significant results were found for sediment Sb, Cd, and TN:TP (Table 3). The non-parametric post-hoc Tukey test ($p < 0.05$) indicated that the Southwestern region has significantly higher concentrations than both the Southeastern region and the Northwestern region for sediment P, and sediment Pb (Table 4, Figure 2). In addition, the Southwestern region has significantly higher concentrations than the Southeastern region for TP, Sb, and a significantly lower TN:TP ratio (Tukey post-hoc, $p<0.05$). Though North Lake in the Southwestern Wind Rivers had the highest concentration of particulate Ca (8 mg L^{-1}) average lake water and sediment concentration were greatest in the Southeastern region and Northwestern region averaging 4-6 mg L^{-1}. Carbonate terrain to the north and east of the WRR likely contributes to high Ca concentrations in the water and sediments of these lakes. Full lake water and sediment chemistry data sets can be found in Supplementary Tables 1 and 2.

Catchment relationships to lake and sediment chemistry

Lake water and sediment chemistry are often related to catchment characteristics in mountainous regions (Kamenik et al. 2001; Maberly et al. 2003; Camarero et al. 2009). To examine these relations in the WRR, we compared lake water sampled in June and bulk sediment elemental chemistry values to catchment characteristics, including percent vegetation type, catchment area, lake area, altitude, and bedrock P concentrations (as an additional factor for consideration of lake TP and SP concentrations) (Supplementary Table 3 and 4). Across all lakes studied we found that DOC in lakes were positively correlated to the percent of forest area in the catchment (r=0.54, p<0.001), and TP concentrations (r=0.41, p<0.05) and negatively correlated to the percent of bare rock (r=-0.66, p<0.001). Carbon and nitrogen concentrations in sediments are negatively correlated to altitude with r of -0.50 and -0.47 respectively at p <0.005. ANC was positively correlated to dissolved Ca (r=0.81, p<0.05), and the CA:LA (r=0.51, p<0.05). Neither TP nor SP was significantly positively correlated to the amount or type of vegetation in the catchment or bedrock-P concentrations. SP was positively correlated to percent bare rock (r=0.51, p<0.005) and lake TP was positively correlated to catchment area (CA) (r=0.35, p<0.05). Bedrock P was negatively correlated to altitude (r=-0.57, p<0.05) and positively correlated to DOC (r =0.63, p<0.001). Across the dust deposition gradient in subalpine and alpine lakes we found DOC was still correlated to percent of catchment forested (r=0.53, p<0.1), but no longer correlated to lake TP. Total phosphorus was positively correlated to steepness (r=0.47, p=0.1), as well as particulate P (PP) (r=0.76, p<0.01), and CA:LA (r=0.69, p<0.01). SP was positively correlated to steepness (r=0.61, p<0.05), and % bare rock (r=0.55, p<0.1), and negatively correlated to % forest (*r*=-0.56, *p*<0.05 Dissolved inorganic nitrogen was positively correlated to % bare rock (*r*=0.86, *p*<0.05), and PP was positively correlated to particulate Ca (*r*=0.51, *p*=0.1), ANC (*r*=0.92, *p*<0.1), and CA:LA (*r*=0.71, *p*<0.05).

USFS Time-series Analysis

Deposition and lake chemistry data for the USFS sampling site at Black Joe Lake, Southwestern region, showed a strong temporal coherence between deposition and lake epilimnion chemistry (Figure 3). Correlation coefficients between deposition and water chemistry at Black Joe Lake for the time period analyzed were 0.58 for pH (*p*< 0.05), 0.35 for Ca^{2+} (*p*<0.1), 0.61 for TN (*p*<0.005), and 0.78 for ANC (*p*<0.005)(Figure 2 a, b, c). Because dust-associated base-cations can contribute to the acid-neutralizing capacity in deposition regions, we might expect Ca^{2+} in deposition to be related to the ANC within the lake. Comparing the trends we see that they covaried with a Pearson correlation coefficient of 0.58, *p*<0.05 (Figure 3 d), and 0.57, *p*<0.001.

Dust in North Lake sediments

The contribution of dust to the lake sediments in North Lake in the Southwestern region of the range was evaluated via $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotopes. Bedrock and dust composition are geochemically distinct, thus the inorganic sediment fraction should be an admixture of dust from the atmosphere and weathered material from the catchment (Figure 4). Based on the surface sediments analyzed, approximately 11% of the 0.25-0.5 cm interval is composed of dust material, and 23% of the 0.5-0.75 cm interval is composed of dust. Given a sedimentation rate of 342 g m^{-2} yr^{-1} for the mineral fraction in these intervals (Brahney 2013) and an average dust fraction of 17%, we estimate a ‘catchment integrated flux’ of 58 g m^{-2} yr^{-1} of dust flux to the lake sediments.

We used the catchment to lake surface area ratio to estimate the amount of material retained within the catchment or delivered to the lake. Using our deposition samplers, we estimated a scaled annual atmospheric dry deposition rate for the region at 3.35 g m^{-2} yr^{-1}. If we assume that all of this material was deposited evenly over the catchment and was transported to the lake surface, then we can use the catchment to lake surface area ratio of 60, to yield a top-down maximum estimate of 200 g m^{-2} yr^{-1} of dust delivered to the lake sediments. Dividing our sediment isotopic estimate by this maximum top-down value (58 g m^{-2} yr^{-1} / 200 g m^{-2} yr^{-1})*100 we determined that approximately 30% of the material is delivered to the lake environment. North Lake’s catchment is quite steep with very little vegetation (Table 1), which would facilitate surface transport and reduce retention of material deposited over the catchment.

Spatial variation in algal populations and relationship to environmental properties

Diatom compositions were distinctly different in both the subalpine and alpine lakes of the Southwestern region in comparison to the subalpine and alpine lakes elsewhere in the WRR and Teton Range. Surface sediment diatom populations in the Southwest tended to have higher concentrations of *Asterionella formosa, Pseudostaurosira pseudoconstruens,* and *Pseudostaurosira brevistriata,* while lakes in other regions tended to have higher concentrations of *Discostella stelligera* and *Stauroseira construens venter*. Similarly, live plankton analysis revealed cell counts of the diatom *A. formosa* to be the highest in Southwestern lakes examined (North and Black Joe lakes) (Table 5).

Unconstrained ordination of diatom species space overlain with environmental factors indicated that SP, lake TP, and pH closely aligned with *A. formosa* and several other species that are common to the Southwestern region (Figure 5). The first two axes explain 56% of the variation and are projected in Figure 5, and the first four axes explain 79% of variation in the diatom data (Supplementary Table 5). In the constrained analysis (CCA), pH, ANC, TP, and sedimentary P are significant at $p < 0.05$, using Holm adjusted p values. TP and SP contributed 25.6 and 24.8 % of the explanatory power in the full model, and explained 12% and 7% of the variation while accounting for the other explanatory variables (conditional effects). The full model is significant at $p<0.005$. The first four axes explained 87% of the fitted variation (Table 7). SP, TP, and pH strongly load on axis 1, suggesting these factors are similarly controlled and play a strong role in species composition throughout these lakes (Figure 6). Species scores for the unconstrained analysis and the CCA are found in Supplementary Table 6 and 7 respectively.

In addition to a unique species composition, biomass was markedly higher in the Southwestern region (Table 5). Phytoplankton biomass was orders of magnitude greater in North Lake, Southwest at 1.3×10^{7} μm^{3} L^{-1} and Black Joe Lake, Southwest at 3.29×10^{6} μm^{3} L^{-1} than lakes in the Northwestern region that had plankton biomass volumes between 4.3 and 5.1 3×10^{5} μm^{3} L^{-1}. Zooplankton biomass was also greater for the Southwestern alpine lakes ranging from 12-40 zooplankers per liter (1-19 μg L^{-1}) compared to only 4 zooplankton per liter (0.1-0.5 μg L^{-1}) in the Northwestern alpine lakes (Table 5).

Discussion

The highest dust deposition rates were found in the Southwestern and West-Central regions of the WRR, the areas closest to the Green River Basin. These results are consistent with the patterns observed by Dahms and Rawlins (1996). Subalpine and alpine lakes in the Southwestern region of the range had the highest concentrations of elements related to atmospheric deposition including TP and sediment concentrations of P, Pb, Sb, Cu, and Cd. Diatom species compositions were also distinctly different in this region, and statistically related to factors that can be controlled by deposition, specifically pH and P. Taken together these results strongly suggest that deposition plays an important role in lake water chemistry and biology in the WRR.

The spatial covariation in dust deposition, lake water chemistry, and sediment chemistry are all strongly suggestive of a causal link between dust deposition and lake biogeochemistry. However, there are two other potential alternative explanations for elevated lake P concentrations. These include catchment characteristics and temperature differences across the lakes. Variations in bedrock P concentrations, catchment morphology, and the type and amount of catchment vegetation across the range could influence lake P concentrations (Kopáček et al. 2011; Prepas et al. 2001; Maberly et al. 2003). The lack of statistical relationships between catchment characteristics, bedrock P concentrations, and lake water and sediment concentrations make this alternative explanation unlikely. Secondly, there could be systematic regional differences in temperature across the range. In this case, warmer temperatures might accelerate nutrient cycling and increase primary productivity in some lakes. This possibility also appears unlikely because long-term lake monitoring of lake temperature (USFS *unpublished data*) does not indicate variations in surface water temperature at Black Joe Lake and does not provide a clear rationale for why the lakes in this region would have elevated TP or SP concentrations.

Several lines of evidence suggest that the dissolved chemistry in the Southwestern region is strongly influenced by atmospheric and, in particular, dust deposition. First, temporal trends in deposition chemistry and lake water chemistry measured at Black Joe Lake over a ~25 year period by the USFS are significantly correlated. In particular dissolved Ca^{2+} in deposition is correlated to dissolved lake Ca^{2+} and alkalinity (Figure 3). Recent studies have shown that dissolved Ca^{2+} in precipitation is a useful indicator of atmospheric dust in this region as it is dominantly derived from mineral sources (Meszaros 1966; Sequiera 1982; Brahney et al. 2013).

Since dust in this region has measurable effects on precipiation alkalinity (Brahney et al. 2013), it would not be surprising to see the same effects on lake water pH and alkalinity. Second, the lakes with the highest SP and lake water TP concentrations are found in the part of the range with the highest rate of dust deposition, and are closest to the Green River Valley dust source. Lakes in the Southwestern region had lake water TP values that ranged from 7 to 12 μg TP L^{-1} (Supplementary Table 1). Within this subset of lakes, North Lake exhibits the greatest TP concentrations measured as high as 14 μg L^{-1}, which is considered “mesotrophic” by most standards (Wetzel 2001). This result is highly unusual for an alpine lake in a silicic basin with over 92% of the basin composed of bare rock. In comparison, subalpine and alpine lakes within the nearby Teton Range have TP values that range from 1.6 to 3.7 μg TP L^{-1}, and the remaining regions in the WRR have TP values that range from 2.3 to 7.6 μg TP L^{-1}. Further, SP concentrations were on average more than twice as high in the Southwestern region than in all other Wind River and Teton lake sediments (Supplementary Table 2).

In many mountainous settings, the phosphorus concentration in lakes declines with increased elevation and loss of catchment vegetation (Kopáček et al. 2011; Müller et al. 1998; Karlsson et al. 2005; Camarero et al. 2009). DOC and P are often highly correlated along these gradients as DOC facilitates the transfer of P to lake systems (Kopáček et al. 2011). In the WRR across an elevation/vegetation gradient we see a similar relationship where TP is significantly correlated to DOC and catchment area. However, PP is strongly correlated to % bare rock and high elevation lakes in the southwestern region have unusually high TP concentrations (7-12 μg L^{-1}), despite low DOC concentrations. Looking at catchment-nutrient relationships in alpine and subalpine lakes across the gradient in dust deposition we find that P concentrations were correlated to factors that facilitate the transport of dust-P to the lake basin, including catchment steepness, CA:LA, and the % of bare rock. Further PP was correlated to regional dust deposition indicators including Ca and ANC. Here our analysis has shown that none of the lake P measurements (TP,PP,SP) were correlated to the amount and/or type of catchment vegetation or soil but significantly and positively correlated to percent bare rock and steepness. These results indicated that subalpine and alpine lake P concentrations are likely linked to an external (atmospheric) source.

Kopáček et al (2011) found that the proportion of atmospheric P delivered to lake basins increased upslope in the Tatra Mountains (due to reduced soil cover). However, even though the soils were sparse and shallow, they were effective at retaining P in these catchments. Phosphorus retention is efficient in the Tatra Mountains due to high concentrations of Al oxyhydroxides and low pH of the soils (Kopáček et al. 2011). Similar results were found in the Sierra Nevada mountains in California (Homyak et al. 2014). In comparison to the Sierra Nevada, moraine soils in the WRR are thin, with lower concentrations of Al oxyhydroxides (Birkeland et al. 1989), and summer precipitation is greater (NOAA 2014). Calculations based on ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr isotopes from the North Lake catchment, a steep and rocky basin, suggested that approximately 30% of the dust material deposited over the entire catchment was delivered to the lake which has the potential to transfer appreciable amounts of P. The steep bare nature of these high altitude catchments combined with high summer precipitation creates an environment where deposited material is more likely to be transported into the water column as opposed to remaining in the catchment. What this suggests is that, in the WRR, steep rocky watersheds have the smallest capacity to take up atmospherically deposited P, and therefore have a lower capacity to ameliorate the effects of atmospheric nutrient deposition.

We found relatively high concentrations of P in the 2010 dust samples measured at 3 mg g^{-1} ± 0.15. Dust samples are typically enriched in P with respect to the upper continental crust average, however, these values are approximately 3x higher than the global average dust P concentration

(Lawrence and Neff 2009). Dahms and Rawlins (1996) measured a high organic content in deposition (40% by weight) as well as the presence of apatite, a P bearing mineral. The high organic content of the soil would likely contain P that is readily available to aquatic organisms, while apatite is relatively insoluble at neutral pH and is not believed to be an important source of P to lakes (Wetzel 2001). However, Smith et al. (1978) were able to demonstrate from culture experiments that bacteria and algae can solubilize natural apatite in alkaline pH. They further showed that both an increase in supply and a decrease in particle size increased production. This indicates that fine-grained apatite contained in atmospheric dust has the potential to be a source of phosphate for lake production. The extent to which dust apatite-P may be utilized by lake microorganisms is an important area of future research.

Patterns in species composition across the study area suggested that lake ecosystems were responding to regional variation in P availability. Species present in large abundances in the subalpine and alpine lakes of the Southwestern region but not present in large abundances elsewhere, included *A. formosa* and *P. brevistriata*. Both constrained and unconstrained ordination analysis revealed close relationships between *A. formosa* and lake water TP and SP concentrations. Both species have previously been identified as mesotrophic species and *A. Formosa* in particular has been known to proliferate in lowland ecosystems polluted with P (Wolin and Stoermer 2005; Barker et al. 2005; Bradshaw et al. 2005; Whitmore 1989; Reavie et al. 1995). Although, *A. formosa* has been noted to appear in alpine lakes where N deposition is high (Wolfe et al. 2003), and is considered an indicator of N pollution in these systems (Saros et al. 2005), the species abundances in the WRR does not appear to covary with N deposition rates or lake water N concentration. This result is similar to that found by Sickman et al. (2013). A recent study by McMurray et al. (2013) found that on the western slope of the WRR, the Southwestern region was the area least impacted by nitrogen deposition, while the West-Central region experienced the highest N deposition rates. This is consistent with our lake water analysis, which indicated that the West-Central and the Northwestern region have the highest lake water TN concentrations (Supplementary Table 1). The proliferation of *A. formosa* in both N and P deposition scenarios can be explained by the fact that this species has been shown to be a good competitor for P when N is in adequate supply (Michel et al. 2006), these results suggest that *A. formosa* is not exclusively an indicator of N deposition in alpine lakes. Similar results were found by Sickman et al. (2013). This finding is important because many portions of the Western US impacted by N deposition are likely also impacted by dust deposition (Brahney et al. 2013).

Alpine lakes in all other regions of the WRR were dominated by the planktonic *D. stelligera* and other small benthic fragilarioid species. Small benthic fragilarioid species are common in colder lakes and typically dominate assemblages from arctic and alpine lakes because they can tolerate extensive ice cover and short growing seasons (Karst-Riddoch et al. 2009). Similarly, *D. stelligera* is considered a circumneutral, oligotrophic species that is common in undisturbed northern lakes (Enache and Prairie 2002; Rühland et al. 2003).

Lakes in the Southwestern region not only had distinct species communities, but species biovolume measurements were two orders of magnitude greater than the alpine lakes in the north, and even higher than the lower elevation lakes in the same region (Table 5). This finding is significant because although dust-P concentrations are high, dust deposition rates in the WRR are in the lower 20th percentile of global measurements that range from <0.1 to >100 g m^{-1} yr^{-2} (Lawrence and Neff 2009), yet this deposition rate appears to be substantial enough to induce ecologically relevant changes.

Sources of dust to the WRR

A recent analysis of continental scale atmospheric deposition by Brahney et al. (2013), suggested that large increases in dust deposition have occurred across much of the Western US in the last few decades, including this region of Wyoming. In fact, visibility data suggest that a doubling in the number of dust storms has occurred in southwest Wyoming in the last decade (Brahney et al. 2013). The spatial gradient of dust deposition with higher rates in the Southwestern region is also consistent with a dust source that is to the south and west of the WRR. The scaled annual deposition rate measured in the Southwestern region of the WRR (3.34 g m^{-2} yr^{-1}) is consistent within the range observed for a “Regional” (10-1000 km)(1.0 to 50 g m^{-2} yr^{-1}) source in a study compiled by Lawrence and Neff (2009). Though dust from Utah is occasionally transported to Wyoming (UDAQ 2009), the most likely dominant source of dust to the Southwestern WRR is from the semi-arid portion of the Green River Basin immediately adjacent to the range.

There are a number of potential factors that can contribute to dust emissions in the semi-arid regions upwind of the WRR. These include factors that control the erosion potential of surface soils (wind speeds), as well as factors that influence the erodability of soils (drought, human land-use). The susceptibility of semi-arid landscapes to erosion is dependent on the interaction between surface properties that act to stabilize soils, e.g. vegetation and soil moisture content, and the erosive force of wind. Drought conditions can increase the availability of soils for transport through a reduction in soil moisture and a decrease in the amount of surface-stabilizing vegetation (Field 2009). Human activities can also destabilize soils and decrease surface vegetation through foot, vehicle, and livestock traffic as well as through industrial activities (Field 2009; Neff et al. 2005). Although data from Brahney et al. (2013) indicate a rise in dust emissions in recent decades, it is unclear whether or not dust emissions from this semi-arid region have always contributed nutrients to lake ecosystems in the Southwestern region of the WRR, or if our observations are a new phenomenon emerging with recent increases in dust deposition.

Conclusions

The data suggest that dust deposition is greatest in the Southwestern region of the WRR, and that dust deposition affects both the lake water chemistry and planktonic species composition. In particular, P concentrations in both lake water and sediments appear to be significantly higher in this region, and statistical methods suggest that diatom species composition is best explained by the spatial distribution of dust related effects including TP and pH. Deposition rates in the WRR are low- to mid-range for what has been measured in other alpine environments, indicating that dust-transfer of nutrients to alpine lakes may be more biologically relevant than previously thought. The results of this study can be extended to other regions that receive large amounts of dust from human and/or natural sources. Because population growth and industrial expansion are expected to continue, the mobilization and subsequent atmospheric transfer of nutrients can be expected to increase apace.

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Table 1. Watershed properties for the Wind River Lakes. Sites are grouped into watershed classifications (Alpine, Subalpine, and Forest, grass or shrub) based on the percent coverage of each landscape type in the respective watersheds, see text for details.

Lake	Catchment Type	CA:LA	% Bare	% Grass	% Forest	Steepness Index (degrees)	Altitude (m)
Southwest Wind River Range							
Arrowhead	Alpine	28	99	1	0	43	3181
Black Joe	Alpine	21	94	2	4	26	3132
North	Alpine	59	91	0	9	38	3085
Deep	Alpine	6	90	7	3	14	3206
Clear	Subalpine	12	77	0	23	13	3057
Big Sandy	Subalpine	34	55	2	43	28	2958
Blue	Forest/Grass	11	38	0	62	4	3115
Diamond	Forest/Grass	29	27	2	71	6	2896
V	Forest/Grass	30	14	3	82	27	2876
Meeks	Forest/Grass	112	9	9	82	10	2840
West-Central Wind River Range							
Hobbs	Forest/Grass	30	49	25	27	7	3074
Barbara	Forest/Grass	11	22	13	67	1	3121
Miller	Forest/Grass	25	0	20	80	3	3074
Sweeny	Forest/Grass	10	0	10	90	2	3133
Eklund	Forest/Grass	50	0	17	83	7	3007
Northwest Wind River Range							
Divide	Alpine	19	95	0	5	3	3257
Marian	Alpine	9	81	0	19	6	3178
Granite Tarn	Subalpine	1	75	0	25	1	3245
Twin North	Subalpine	10	63	0	37	6	2999
Shirley	Forest/Grass	14	41	0	59	8	3048
Twin South	Forest/Grass	10	18	0	82	3	3001
Seiglers	Forest/Grass	176	14	73	13	5	3062
Horseshoe	Forest/Grass	12	0	0	100	3	3007
Dollar Lake	Forest/Grass	61	0	0	100	4	3021
Grass	Forest/Grass	9	0	54	46	4	2996
Flat	Forest/Grass	138	0	98	2	5	3086
Southeast Wind River Range							
Lonesome	Alpine	32	81	10	10	21	3093
Cook	Subalpine	19	64	10	26	14	3070
Smith	Subalpine	13	59	0	41	18	2976
Middle	Forest/Grass	11	31	0	69	9	3028
Clover	Forest/Grass	6	30	0	70	5	3035

Table 2. Summer dust deposition from bulk deposition collectors in the Wind River Range (2009 and 2010). Annual deposition rates are scaled up from summer deposition rates.

Wind River Range Location	Latitude	Longitude	masl	Sampling intervals	Deposition Rate mg m^{-2} yr^{-1}	Avg. Annual Deposition Rate g m^{-2} yr^{-1}
Southwest	42.73	-109.16	3130	07/03/2009-07/13/2009	3.45	3.34
				07/13/2009-08/13/2009	7.42	
				08/13/2009-09/03/2009	10.11	
				09/03/2009-09/10/2009	10.93	
				06/27/2010-08/16/2010	6.10	
				08/16/2010-09/04/2010	16.97	
West-Central	43.03	-109.67	3070	06/29/2010-09/03/2010	8.22	3.00
Northwest	43.36	-109.76	3071	07/23/2009-08/16/2009	3.62	1.06
				08/16/2009-09/09/2009	2.18	

Table 3. Kruskal-wallis test results for selected chemical constituents in June lake water and bulk sediments for lakes in the Wind River Range. Significant results are highlighted with asterisks (*p*<0.1).

	June lake water			Bulk Sediment						
	TP	Ca	TN:TP	P	Cd	Cu	Cr	Sb	Pb	Ca
χ2	4.69	4.26	0.21	8.03	4.30	2.75	5.99	4.39	5.27	10.39
p	0.096*	0.890	0.118	0.018*	0.116	0.252	0.05*	0.111	0.071*	0.005*

Table 4. Test statistic and *p*-values for the non-parametric post-hoc contrast effect test for differences in sediment and lake chemistry between regions. SE=Southeast, SW=Southwest, NW=Northwest. Significant results are highlighted with asterisks (*p*<0.1).

	June Lake Water				Bulk Sediment									
	TP		TN:TP		P		Pb		Sb		Cd		Cu	
	Statistic	*p*	Statistic	*p*	Statistic	*p*	Statistic	*p*	Statistic	*p*	Statistic	*p*	Statistic	*p*
SE-NW	0.31	0.977	-0.65	0.855	-1.79	0.170	0.31	0.966	0.92	0.640	0.00	1.000	-2.67	0.985
SE-SW	2.96	0.009*	-568.90	<0.001*	5.65	<0.001*	3.13	0.005*	2.55	0.026*	2.00	0.094*	0.62	0.861
NW-SW	2.30	0.056*	-0.53	0.914	7.78	<0.001*	2.84	0.011*	2.05	0.096*	2.40	0.033*	2.00	0.115

Table 5 Water column plankton for lakes in the Southwest, West-Central, and Northwest. USFS data was collected between Aug 2006 and Aug 2007 (Miller 2009)

Wind River Range Location	Lake	Phytoplankton cell L^{-1}	Phytoplankton Biovolume $\mu m^3 L^{-1}$	*A. formosa* cell L^{-1}	Zooplankton α-diversity	Zooplankton L^{-1}	Zooplankton Biomass μg L^{-1}
Southwest	North	27000	$1.26x10^7$	4260	0.89	24	19.31
	Black Joe	7700	$3.3x10^6$	6300	0.80	40	1.00
	Black Joe[a]					18-32	
	Meek	3000	$1.8x10^6$	150	0.62	73	82.86
	Deep[a]					12-24	
Northwest	Divide	830	$5.1x10^5$	760	0.63	4	0.46
	Twin S	118	$4.3x10^5$	3	0.75	4	0.12
West-Central	Hobbs[a]					3-4	

[a] USFS data.

Fig.1 The Wind River Range and the Teton Range sampling areas in western Wyoming. Black circles represent the 32 lakes that were sampled in this study. The primary dust source, the northern portion of the Green River Valley is located to the south and west of the Wind River Range. Wind rose data from the Western Regional Climate Center (1985-2014)(WRCC 2014)

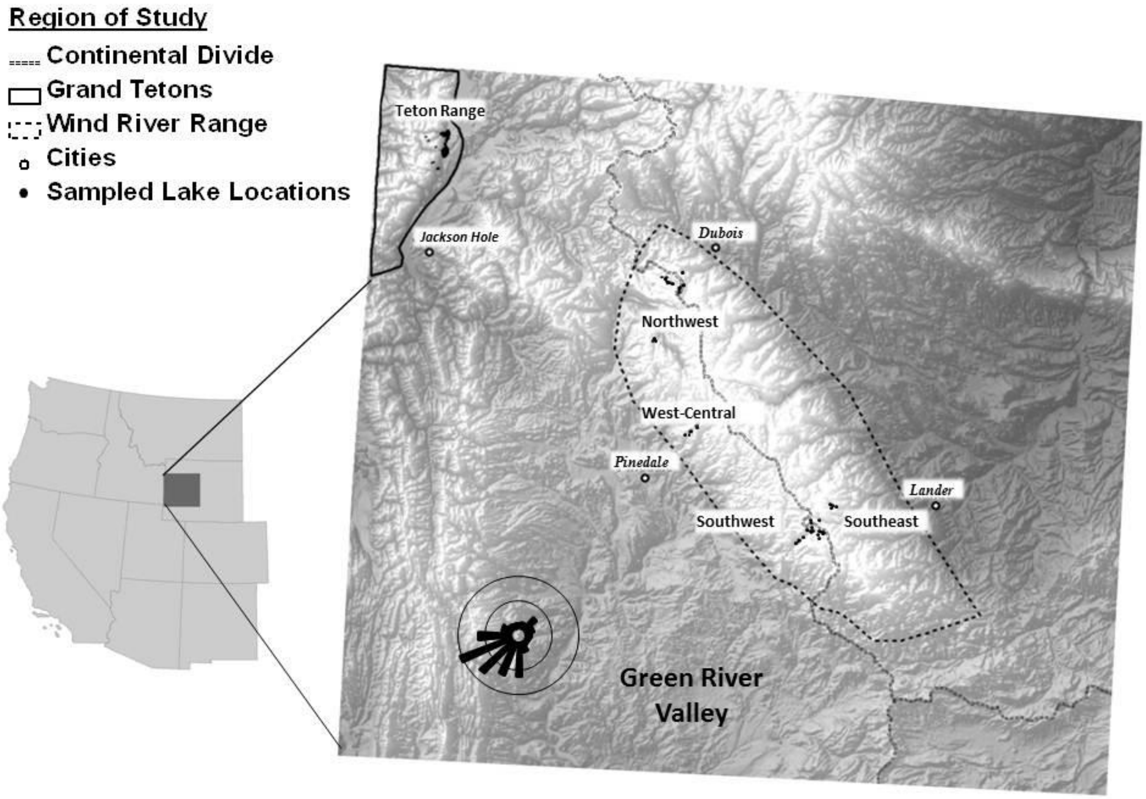


Fig.2 Box-plots of alpine and subalpine lake water and bulk sediment concentrations of select elements across three regions of the Wind River Range. Letters indicated significant differences between regions using a non-parametric post-hoc contrast test (*p*<0.05). Overall Kruskal-Wallis significance is shown in each plot. Southwest, n=6, Northwest n=4, Southeast n=4

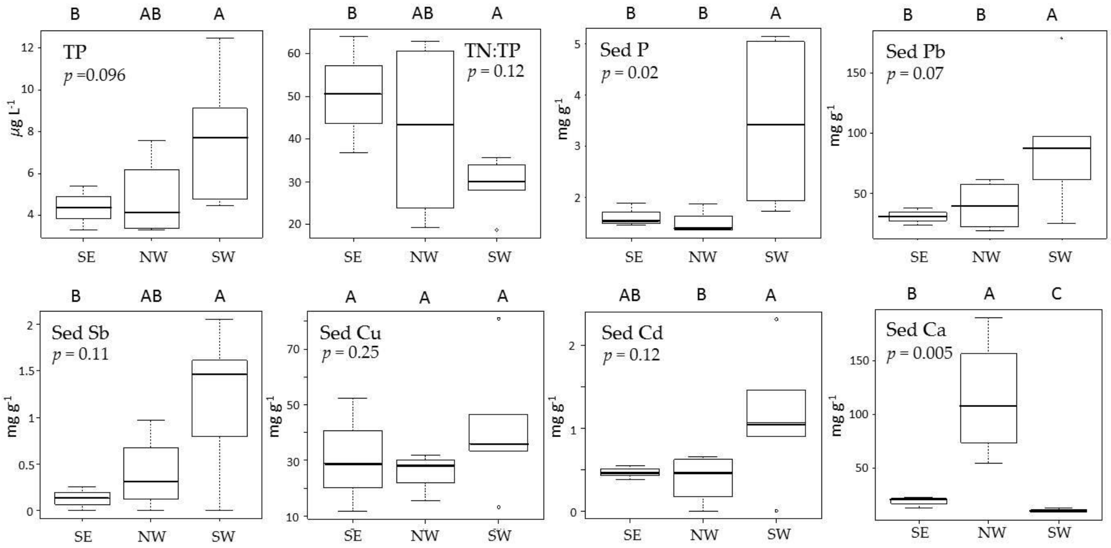


Fig. 3 Nutrient concentration and pH of deposition and epilimnion water samples. Panels are a) pH, b) TN, and c) Ca^{2+} d) Ca^{2+} and ANC for Black Joe Lake in the Southwestern region, Wind River Range, Wyoming. Measurements for all variables except the pH and ANC of the epilimnion are annual averages

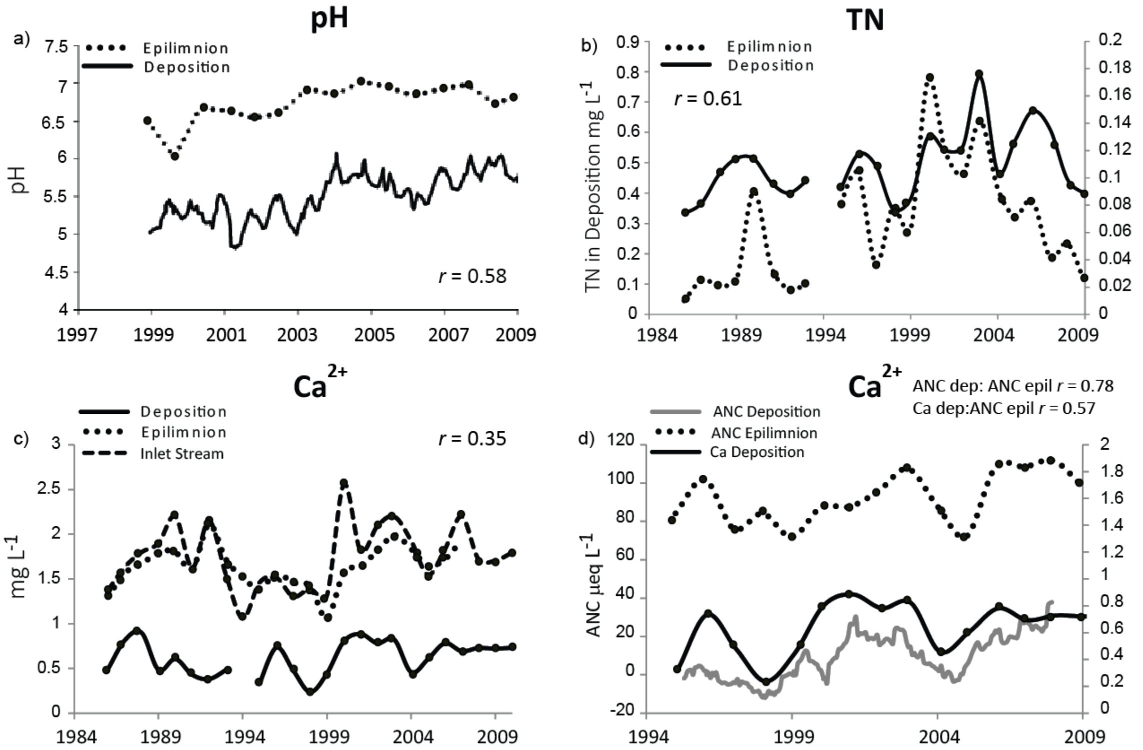


Fig. 4 $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope composition of bedrock, sediment, and dust for the North Lake catchment, Southwestern region in the Wind River Mountains.

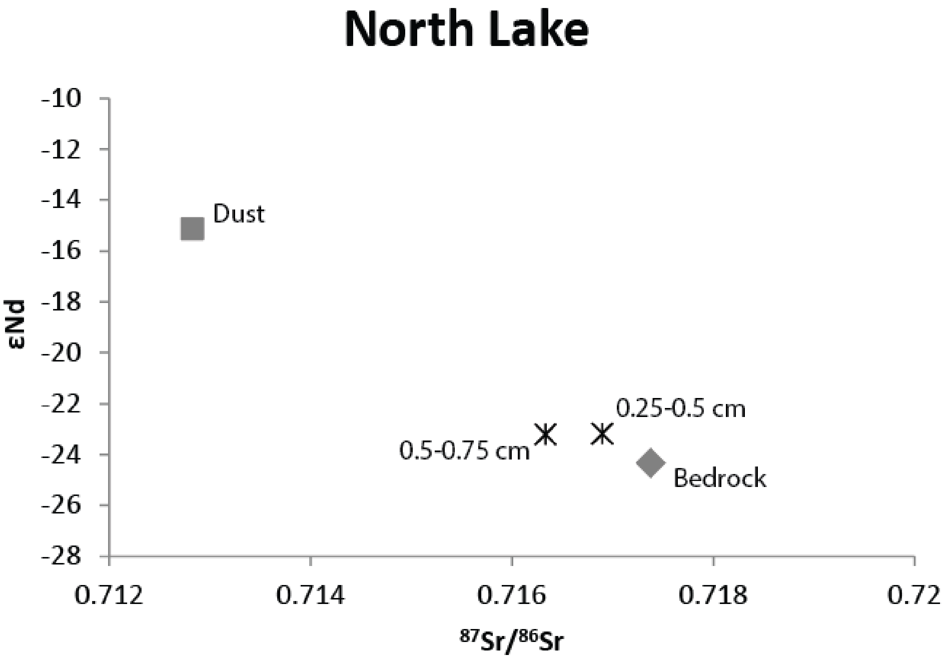


Fig. 5 Unconstrained ordination plot for species data overlain with environmental factors for 18 alpine and subalpine lakes in the Wind River and Teton Ranges. Sites grouped by regions are also plotted; note there were no alpine or subalpine sites in the West-Central region

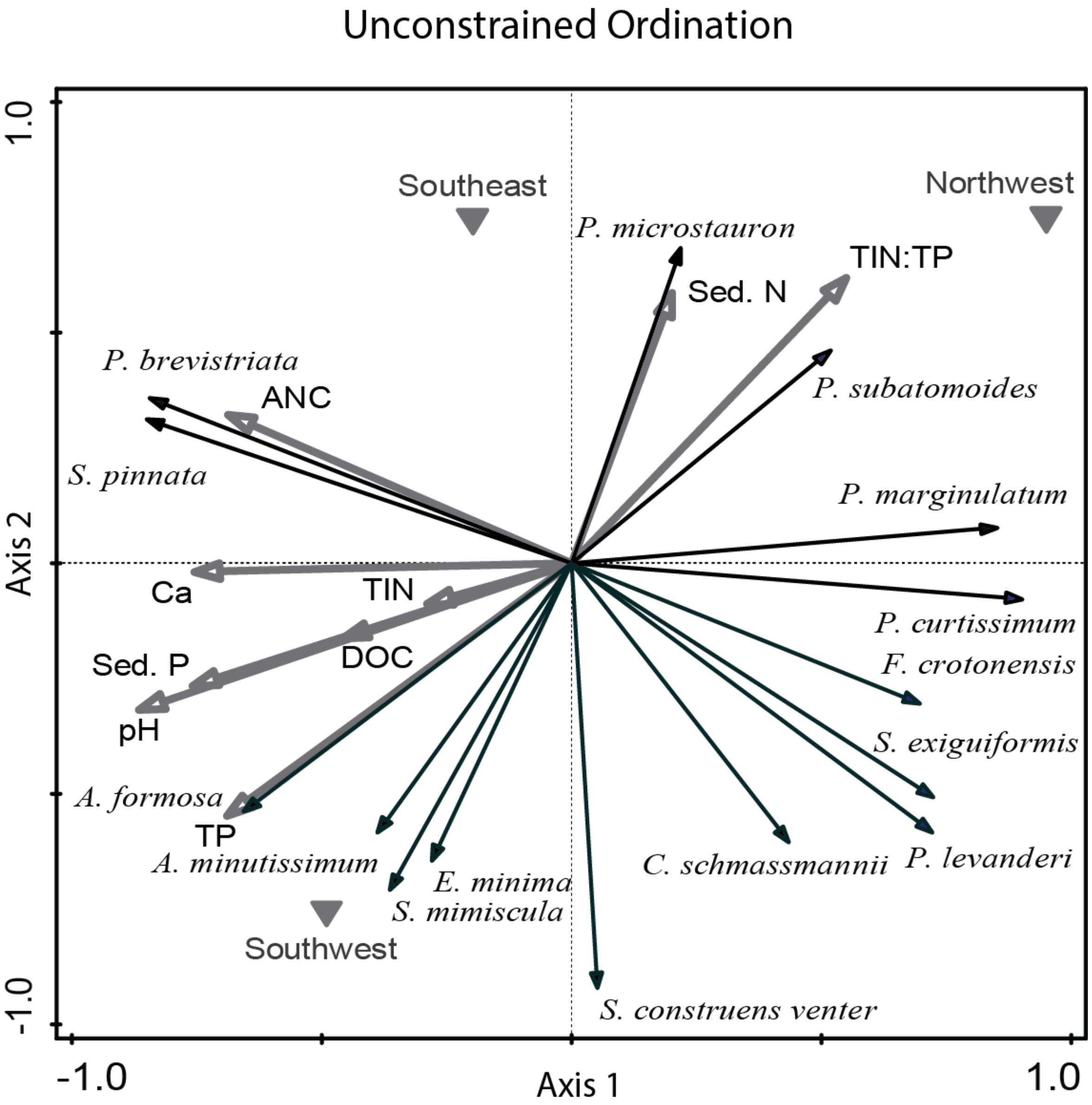
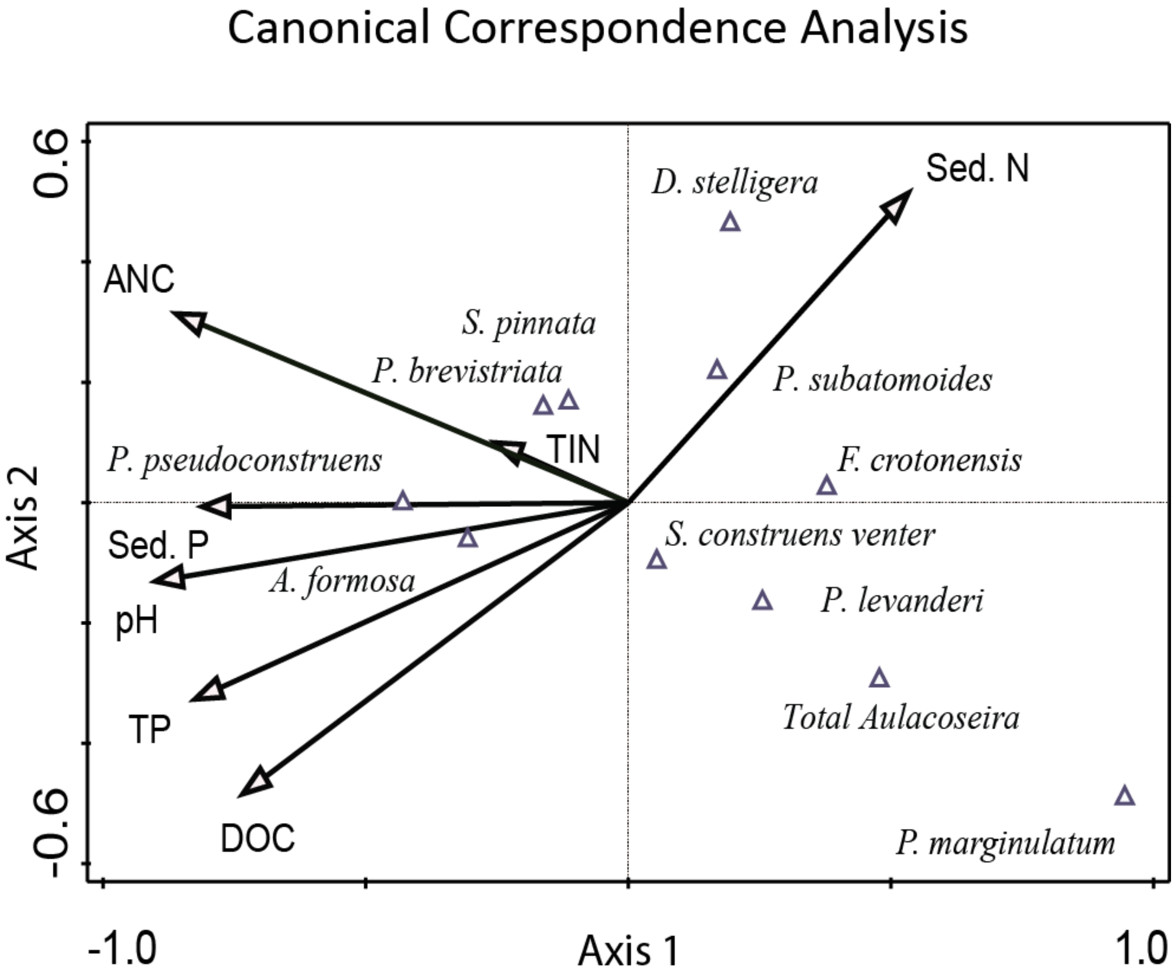


Fig. 6 Canonical correspondence analysis (CCA) of the 18 alpine and subalpine lakes in the Wind River and Teton Ranges showing species scores in ordination space. Arrows represent the variables that exert significant influence on the diatom species distributions at the *p*<0.05 (ANC, Sed. P, TP, pH, DOC), *p*<0.1 (Sed. N) level. Though DIN was not significant it is included in the plot due to its previous association with *A. formosa*



Supplementary Table 1 Dissolved and particulate chemistry for 38 lakes sampled during spring mixing in the Wind River and Teton Ranges of Western Wyoming

Lake	TN (μg L^{-1})	DIN (μg L^{-1})	TP (μg L^{-1})	Particulate P (μg L^{-1})	lake TN:TP	Particulate N:P	DOC (mg C L^{-1})	ANC (μeq L^{-1})	pH	Particulate Ca (μg L^{-1})	Dissolved Ca (μg L^{-1})
Southwest Wind River											
Arrowhead	139		4.5	0.85	31	11	1.62		7.66	5623	4315
Black Joe	256	48	9.1	0.72	28	3	1.71	101	7.11	2563	1669
North	234	58	12.5	5.43	19	3	1.88	144	7.19	8378	3447
Deep	255		7.1	0.55	36	10	2.10		7.14		2163
Clear	163	32	4.8	0.10	34	73	1.58	86	7.00	3777	1748
Big Sandy	240	23	8.3	0.68	29	21	2.75	114	7.15	3278	2353
Blue	136		2.7		50		1.62	75	6.99	946	1633
Diamond	235	21	8.8		27		5.36	123	6.91	238	2374
V	213	67	10.0	0.04	21	210	5.76	180	7.05	356	2637
Meeks	328	33	9.0	0.01	36	476	7.52	254	7.15	593	3371
West-Central Wind River											
Hobbs	234	7	9.2		25		3.33	95	6.52		1992
Barbara	275	35	10.6		26		4.65	90	6.54		2095
Miller	267		5.7		47		5.74	163	6.56		
Sweeny	511		6.8		85		7.31	104	6.64		
Eklund	290		17.9		16		4.68	98	6.37		
Northwest Wind River											
Divide	147		7.6	2.07	19	8	1.22		7.81	2377	1573
Marian	208		3.3	0.68	63	5	2.61		7.59	5245	2378
Granite Tarn	137		4.8	1.00	29	6	1.23		8.08	4002	1456
Twin L. North	201		3.4	0.45	58	75	1.63		7.1	7732	13436
Shirley	1101		5.3	0.79	207	29	1.06		7.1	2461	14177
Twin L. South	1145		2.3		498		1.21		7.1	4959	13919
Seidlers (No name)	174		4.6	0.69	38		3.21		7.88	5618	2851
Horseshoe	114		7.2	0.29	16	12	2.13		7.99	988	2307
Flat	201		11.3	0.93	18	23	4.10		7.72	4913	2597
Dollar	180		6.6	0.21	27	128	2.58		8.10	3103	2140
Grass	342		14.6	0.46	23	54	4.65		8.20	3509	3058
Southeast Wind River											
Lonesome	162		4.4	0.25	37	18	1.07		7.39	3028	2458
Cook	273	32	5.4		51		2.23	143	6.84		3029
Smith	211	35	3.3		64		2.85	148	6.86		2851
Middle	376	56	4.5		83		3.44	162	6.905		2996
Clover	334	19	5.0		67		4.15	207	6.955		3285
Lizard Head	205		NA		21		4.36		7.40	4797	3268
Teton Range											
Surprise	71		1.1		63		0.78	51	6.46		613
Grizzly	69	32	0.9		79		0.49	119	6.93		2037
Ramshead	111	61	0.8		142		0.53	73	6.60		1102
Holly	53	16	0.7		74		0.60	98	6.77		1405
Amphitheatre	78	31	1.1		72		0.52	49	6.52		686
Whitebark (No Name)	98		1.7		59		1.86	85	6.67		1242

Supplementary Table 2 Bedrock and sediment chemistry for 38 lakes in the Wind River and Teton Ranges of Western Wyoming

Lake	Bedrock P (mg g^{-1})	Sediment P (mg g^{-1})	Sediment % N	Sediment % C	Sediment C:N	Sediment N:P	Sediment Pb (mg g^{-1})	Sediment Sb (mg g^{-1})	Sediment Cu (mg g^{-1})	Sediment Cd (mg g^{-1})	Sedimen Ca (mg ^{1})
Southwest Wind River											
Arrowhead	0.2	4.56	0.80	8.26	10	1.75	178.51	2.05	80.88	2.31	11.62
Black Joe		1.74	0.15	1.79	12	0.89	25.37	0.00	13.28	0.00	12.98
North	0.98	5.04	0.67	6.96	10	1.34	82.74	1.62	46.55	0.90	9.58
Deep		5.15	0.43	4.72	11	0.84	97.60	1.41	33.55	1.17	9.17
Clear	0.39	2.29	0.49	6.34	13	2.13	92.57	1.50	38.15	1.46	11.06
Big Sandy	0.42	1.93	0.81	8.97	11	4.21	61.67	0.79	33.99	0.96	9.20
Blue	1.56	3.36	1.14	11.46	10	3.39	110.37	2.21	42.80	1.49	6.57
Diamond	2.16	1.95	1.05	13.24	13	5.42	63.69	1.05	34.84	0.66	6.72
V	1.65	1.49	1.72	15.09	9	11.55	38.07	0.35	22.78	0.77	6.30
Meeks	1.26	1.42	0.76	9.10	12	5.34	21.94	0.00	16.30	0.00	13.51
West-Central Wind River											
Hobbs		1.09	1.11	14.15	13	10.88	52.38	0.47	15.56	0.22	78.66
Barbara		1.81	0.04	0.61	17	0.20	9.28	0.00	6.95	0.00	17.56
Miller		1.80	0.47	6.91	15	2.61	39.65	0.08	17.52	0.44	18.48
Sweeny		1.18	0.44	7.69	18	3.68	14.80	0.00	7.31	0.23	8.43
Eklund		1.68	0.45	7.30	16	2.18	25.05	0.00	14.59	0.38	20.62
Northwest Wind River											
Divide	0.18	1.42	0.72	6.64	9	5.05	61.53	0.97	28.51	0.59	54.97
Marian		1.87	0.12	1.72	15	0.63	19.52	0.00	31.80	0.00	189.98
Granite Tarn		1.38	0.29	3.17	11	2.12	25.45	0.25	15.58	0.35	122.72
Twin L. North	0.96	1.36	1.90	19.96	11	13.99	54.48	0.39	28.25	0.66	92.61
Shirley	0.06	2.38	1.55	17.73	11	6.50	50.28	0.41	33.29	0.69	71.30
Twin L. South	0.96	1.38	1.48	12.08	8	10.70	51.96	0.34	28.47	1.06	97.56
Seidlers (No name)		0.99	0.78	8.84	11	7.94	25.58	0.34	29.49	0.62	98.45
Horseshoe	0.11	1.10	0.19	1.73	9	1.77	16.89	0.00	27.98	0.50	70.33
Flat		1.75	0.91	9.09	10	5.21	17.37	0.00	17.62	0.36	9.44
Dollar	0.3	1.32	1.24	15.25	12	9.42	54.33	1.18	36.74	1.27	78.10
Grass	0.09	1.37	1.19	18.11	15	8.68	22.24	0.00	29.07	1.01	9.59
Southeast Wind River											
Lonesome		1.88	0.25	3.03	12	1.35	38.00	0.26	28.86	0.55	21.07
Cook		1.54	0.39	3.55	9	2.56	31.46	0.00	11.65	0.39	23.10
Smith		1.45	0.99	13.82	14	7.43	23.87	0.13	52.40	0.47	13.55
Middle		1.76	0.59	6.26	11	3.34	72.65	1.17	35.18	0.93	9.51
Clover		2.26	1.32	12.86	10	5.83	86.89	1.17	34.50	1.35	106.05
Lizard Head	2.26	1.01	0.82	11.49	14	8.12	32.57	0.26	23.07	0.00	10.37
Teton Range											
Surprise		0.51	0.11	1.05	9	0.22					
Grizzly		0.66	0.22	2.11	10	0.33					
Ramshead		1.53	0.20	1.97	10	0.13					
Holly		1.70	0.31	2.46	8	0.18					
Amphitheatre		0.68	0.23	1.84	8	0.34					
Whitebark (No Name)		1.41	0.19	1.75	9	0.14					

Supplementary Table 3. Pearson correlation matrix for select lake and sediment chemistry variables and catchment properties across elevation gradients for 32 lakes in the Wind River Range. Stars indicate significance at * *p*<0.1, ***p*<0.05, * *p*<0.01, *italic*s for *p*=0.1.**

	Sediment P (mg g^{-1})	Dissolved TP (μ g L^{-1})	Sediment % N	Sediment % C	DIN (μ g L^{-1})	lake TN:TP	DOC (mg C L^{-1})	ANC (μ eq L^{-1})	pH	Part. Ca (mg L^{-1})	Ca (mg L^{-1})	Bedrock P (ppm)	Altitude (masl)	Lake Area (km^2)	Catchment Area (km^2)	Catchment: Lake Area	% Bare Rock	% Grass/ Shrub	% Forest
Sediment P (mg g^{-1})	1.00																		
Dissolved TP (μ g L^{-1})	0.05	1.00																	
Sediment % N	-0.06	-0.18	1.00																
Sediment % C	-0.12	-0.13	0.95***	1.00															
DIN (μ g L-1)	0.35	0.22	-0.05	-0.24	1.00														
lake TN:TP	-0.09	-0.39**	0.36**	0.25	0.00	1.00													
DOC (mg C L^{-1})	*-0.29*	0.41**	-0.02	0.09	-0.03	-0.22	1.00												
ANC (μ eq L^{-1})	-0.10	-0.10	0.34	0.26	0.20	0.20	0.48**	1.00											
pH	-0.04	-0.26	-0.04	-0.12	*0.44*	-0.11	-0.42**	0.35	1.00										
Particulate Ca (mg L^{-1})	0.34	-0.14	0.03	0.01	0.27	0.13	-0.43*	-0.2	0.15	1.00									
Ca (mg L^{-1})	-0.09	-0.37*	0.66*	0.62***	0.27	0.74***	-0.25	0.81**	-0.3	0.32	1.00								
Bedrock P (ppm)	-0.07	0.28	0.36	*0.40*	0.14	-0.05	0.63***	0.20	-0.57**	-0.32	-0.04	1.00							
Altitude (masl)	0.31*	-0.18	-0.47***	-0.50***	-0.03	-0.11	-0.47***	-0.61***	*0.28*	0.37	-0.22	-0.52**	1.00						
Lake Area (km^2)	0.11	0.03	-0.31*	-0.33***	0.21	-0.18	-0.23	-0.16	-0.10	-0.26	-0.35	-0.24	-0.02	1.00					
Catchment Area (km^2)	-0.15	0.35*	-0.14	-0.16	0.16	-0.26	0.03	-0.04	0.05	-0.12	-0.36	-0.03	-0.29	0.62***	1.00				
Catchment:Lake Area	-0.14	*0.31*	0.06	0.07	0.08	-0.19	0.28	0.51**	0.30*	0.15	-0.18	0.21	-0.24	-0.23	0.49***	1.00			
% Bare Rock	0.51***	-0.24	-0.21	-0.27	0.09	-0.13	-0.66***	-0.27	0.16	0.39*	-0.13	-0.42*	0.54***	0.37**	0.02	-0.34*	1.00		
% Grass/Shrub	-0.19	0.25	-0.04	-0.03	*-0.47*	-0.15	0.22	-0.11	0.14	0.21	-0.13	0.29	0.03	-0.18	0.37**	0.80***	-0.35**	1.00	
% Forest	-0.41**	0.08	0.24	0.29	0.03	0.23	0.54***	0.33	-0.26	-0.56**	0.23	*0.41*	-0.57***	-0.27	-0.25	-0.16	-0.80***	-0.28**	1.00

Supplementary Table 4. Pearson correlation matrix for select lake and sediment chemistry variables and catchment properties across dust gradients for 13 lakes in the Wind River Range. Stars indicate significance at * *p*<0.1, ***p*<0.05, * *p*<0.01, *italic*s for *p*=0.1.**

	Sediment P (mg g^{-1})	Dissolved TP (µ g L^{-1})	Steep. I.	Sediment % N	Sediment % C	DIN (µ g L^{-1})	*Part. P (µ g* L-1)	lake TN:TP	DOC (mg C L^{-1})	ANC (µ eq L-1)	pH	Ca (mg L^{-1})	Part. Ca (mg L^{-1})	Bedrock P (ppm)	Altitude (masl)	Lake Area (km^2)	Catchment Area (km^2)	Catchment :Lake Area	% Bare Rock	% Grass/ Shrub	% Forest
Sediment P (mg g^{-1})	1.00																				
Dissolved TP (µ g L^{-1})	0.45	1.00																			
Steepness Index	0.61**	*0.47*	1.00																		
Sediment % N	-0.07	-0.17	0.00	1.00																	
Sediment % C	-0.10	-0.24	0.00	0.98***	1.00																
DIN (µ g L-1)	0.72	0.67	0.62	-0.27	-0.27	1.00															
Particulate P (µ g L^{-1})	0.45	0.76***	0.37	0.05	0.00	0.77	1.00														
lake TN:TP	-0.38	-0.73***	-0.35	0.27	0.36	-0.44	-0.50	1.00													
DOC (mg C L^{-1})	0.02	-0.03	0.14	0.07	0.17	-0.51	0.00	0.53*	1.00												
ANC (µ eq L^{-1})	0.21	0.04	0.23	0.49	0.40	0.23	0.92*	0.43	0.55	1.00											
pH	-0.03	-0.09	-0.23	-0.24	-0.31	0.41	0.05	-0.37	-0.51*	-0.32	1.00										
Ca (mg L^{-1})	-0.10	-0.30	-0.08	0.90***	0.90***	0.51	-0.07	0.53*	-0.04	0.96**	-0.27	1.00									
Particulate Ca (mg L^{-1})	0.56*	0.08	0.24	*0.55*	*0.55*	0.66	0.51*	0.30	0.18	0.83	-0.20	0.65**	1								
Bedrock P (ppm)	0.29	0.42	0.25	0.66*	0.67*	0.96	0.48	0.07	0.06	0.89	-0.68*	0.66*	0.79**	1.00							
Altitude (masl)	0.22	0.06	-0.26	-0.50*	-0.58**	0.69	0.07	-0.40	-0.51**	-0.23	0.77***	-0.46	-0.26	-0.65*	1.00						
Lake Area (km^2)	-0.06	0.20	0.13	-0.33	-0.25	-0.29	-0.38	0.01	0.36	-0.55	-0.55*	-0.38	-0.58*	-0.14	-0.28	1.00					
Catchment Area (km^2)	-0.19	0.37	0.40	-0.22	-0.19	-0.29	-0.17	-0.20	0.27	-0.41	-0.41	-0.29	-0.49	0.05	-0.47	0.77***	1.00				
Catchment:Lake Area	0.42	0.69***	0.78***	0.02	-0.02	0.58	0.71**	-0.49*	-0.01	0.33	-0.15	-0.07	0.30	0.50	-0.27	-0.12	0.34	1.00			
% Bare Rock	0.55*	0.37	0.27	-0.39	-0.46	0.86**	0.34	-0.56**	-0.53*	-0.28	0.45	-0.37	-0.05	-0.26	0.75***	-0.14	-0.24	0.20	1.00		
% Grass/Shrub	0.06	-0.03	0.05	-0.34	-0.38	-0.31	-0.31	0.06	-0.05	0.27	-0.31	-0.20	-0.39	-0.11	-0.04	0.33	0.29	0.05	-0.09	1.00	
% Forest	-0.56**	-0.36	-0.28	*0.47*	0.55**	-0.82**	-0.26	0.54*	0.53*	0.22	-0.37	0.40	0.13	0.27	-0.74***	0.05	0.17	-0.21	-0.97***	-0.16	1.00

Supplementary Table 5. Eigenvalues and percent of fitted variance for the first four axis of the unconstrained ordination analysis and the Canonical Correspondence Analysis (CCA) for the 18 alpine and subalpine lakes from the Wind River and Teton Ranges

	Axis 1	Axis 2	Axis 3	Axis 4
Unconstrained ordination analysis				
Eigenvalues	0.317	0.239	0.136	0.095
% of fitted variance	33.3	24.9	14.0	10.1
Cumulative % of fitted variance	33.3	58.2	72.2	82.3
Canonical Correspondence Analysis (CCA)				
Eigenvalues	0.337	0.220	0.153	0.095
% of fitted variance	36.2	20.6	15.6	9.7
Cumulative % of fitted variance	34.3	56.8	72.3	82.1

Supplementary Table 6. Species scores for the first four axis of the unconstrained ordination analysis of 31 alpine and subalpine lakes from the Wind River and Teton Ranges.

	Axis 1	Axis 2	Axis 3	Axis 4
Asterionella formosa	-0.656	-0.539	-0.127	-0.068
Pseudostaurosira brevistriata	-0.845	0.358	0.242	0.142
Staurosira construens var venter	0.052	-0.921	-0.104	0.132
Staurosira pinnata	-0.851	0.312	0.052	-0.028
Achnanthidium minutissimum	-0.388	-0.585	0.311	0.237
Total Aulacoseira	0.676	0.122	-0.419	0.498
Cavinula pseudoscutiformis	-0.170	-0.530	0.366	-0.183
Chamaepinnularia indifferens	0.717	-0.229	0.082	0.458
Chamaepinnularia schmassmannii	0.435	-0.605	0.507	0.196
Discostella stelligera	0.075	0.556	0.687	0.231
Diatoma anceps	0.579	-0.615	0.145	0.033
Encyonema silesiacum	-0.299	-0.447	0.092	0.006
Encyonema minutum	-0.077	-0.573	0.535	0.163
Encyonema neogracile	0.449	-0.341	0.139	-0.052
Eolimna minima	-0.280	-0.645	0.385	0.094
Eolimna subminiscula	-0.076	-0.669	-0.092	-0.556
Eolimna subrotunda	-0.019	-0.551	0.664	0.323
Karayevia suchlandtii	-0.001	-0.041	0.403	0.539
Navicula aff.sp.3	0.595	-0.323	0.197	-0.292
Navicula digitulus	0.584	-0.110	-0.147	-0.148
Stauroforma exiguiformis	0.725	-0.508	0.103	-0.159
Frag_cap_grac	-0.357	-0.532	0.425	0.334
Fragilaria crotonensis	0.698	-0.304	-0.174	-0.177
Fragilaria vaucheriae	-0.100	-0.467	0.217	-0.063
Gomphonema gracile	-0.109	-0.392	0.105	-0.062
Hannaea arcus	-0.099	-0.470	0.222	-0.063
Navicula leptostriata	0.010	-0.374	0.549	0.554
Navicula radiosa	-0.131	-0.542	0.502	0.203
Navicula rhynocephala	-0.442	-0.659	0.147	0.210
Nitzschia bacillium	0.048	-0.397	0.499	0.165
Nitzschia fonticola	-0.371	-0.695	0.411	-0.016
Nitzschia dissipata	-0.099	0.283	-0.096	0.905
Nupela vitiosa	-0.187	0.658	-0.081	-0.208
Pinnularia microstauron nonfasciata	0.218	0.684	0.196	-0.653
Navicula seminulum	0.549	-0.346	-0.074	-0.555
Pseudostaurosira curtissimum	0.903	-0.078	-0.047	-0.378
Pseudostaurosira daonense	0.852	0.077	-0.188	-0.204
Pseudostaurosira didymum	-0.076	-0.606	0.403	0.021
Pseudostaurosira helveticum	0.353	-0.596	0.359	0.188
Pseudostaurosira levanderi	0.724	-0.584	0.289	0.087
Pseudostaurosira marginulatum	0.765	0.093	-0.329	0.418
Pseudostaurosira subatomoides	0.519	0.461	0.386	-0.587
Pseudostaurosira rechtensis	-0.448	-0.109	-0.070	0.228
Pseudostaurosira pseudoconstruens	-0.654	-0.050	-0.569	0.338
Rossthidium pusillum	-0.067	-0.500	0.541	0.023
Sellaphora miniscula	-0.364	-0.709	0.314	-0.114
Sellaphora pupula	-0.150	0.091	0.010	-0.567
Sellaphora laevissima	-0.223	0.208	-0.218	-0.612
Staurosirella oldenburgiana	-0.407	-0.106	-0.181	-0.539
Tabellaria flocculosa	-0.127	-0.623	0.348	0.120
Pinnularia interrupta	-0.283	-0.558	0.282	0.273
Fragelaria elliptica	-0.582	-0.132	-0.478	-0.084
Pseudostaurosira parasitica	-0.063	-0.291	0.419	0.382
Eolimna submuralis	-0.480	-0.475	0.040	0.115
Nitzschia inconspicua	-0.429	-0.185	-0.221	-0.212

Supplementary Table 7. Species scores for the first four axis of the Canonical Correspondence Analysis (CCA) of 31 alpine and subalpine lakes from the Wind River and Teton Ranges.

	Axis 1	Axis 2	Axis 3	Axis 4
Asterionella formosa	-0.716	-0.165	0.183	-0.023
Pseudostaurosira brevistriata	-0.248	0.400	0.090	-0.055
Staurosira construens var venter	0.089	-0.167	-0.142	-0.316
Staurosira pinnata	-0.384	0.370	0.236	0.056
Achnanthidium minutissimum	-0.468	-0.182	-0.265	-0.009
Total Aulacoseira	1.097	-0.699	0.775	0.216
Cavinula pseudoscutiformis	-0.200	-0.230	-0.036	0.498
Chamaepinnularia indifferens	0.984	-0.568	-0.058	-0.544
Chamaepinnularia schmassmannii	0.506	-0.419	-0.459	-0.282
Discostella stelligera	0.394	1.108	-0.730	-0.097
Diatoma anceps	0.612	-0.878	-0.025	0.065
Encyonema silesiacum	-0.746	-0.402	-0.190	0.515
Encyonema minutum	0.277	0.022	-0.635	-0.058
Encyonema neogracile	0.670	-0.859	0.247	0.207
Eolimna minima	-0.030	-0.086	-0.550	-0.476
Eolimna subminiscula	-0.022	-0.079	0.221	-0.088
Eolimna subrotunda	-0.292	-0.592	-0.502	0.158
Karayevia suchlandtii	-0.146	-0.233	-0.046	0.421
Navicula aff.sp.3	0.608	-0.380	0.450	0.239
Navicula digitulus	0.588	-0.232	0.783	-0.041
Stauroforma exiguiformis	0.597	-0.254	-0.031	0.107
Frag_cap_grac	-0.628	-0.351	-0.060	-0.235
Fragilaria crotonensis	0.837	0.062	-0.311	-0.082
Fragilaria vaucheriae	-0.451	-0.660	-0.677	1.172
Gomphonema gracile	-0.546	-0.677	-0.770	1.496
Hannaea arcus	-0.456	-0.661	-0.682	1.189
Navicula leptostriata	-0.232	-0.681	-0.689	0.479
Navicula radiosa	-0.469	-0.520	-0.380	0.322
Navicula rhynocephala	-0.590	-0.396	-0.155	-0.098
Nitzschia bacillium	0.134	-0.728	-0.751	-0.665
Nitzschia fonticola	-0.621	-0.356	-0.070	-0.222
Nitzschia dissipata	-0.528	-0.332	-0.032	-0.798
Nupela vitiosa	0.109	0.778	0.174	0.465
Pinnularia microstauron nonfasciat	0.578	1.123	0.383	0.286
Navicula seminulum	0.427	0.071	0.077	0.084
Pseudostaurosira curtissimum	0.944	0.053	0.147	-0.051
Pseudostaurosira daonense	1.447	0.108	0.618	0.026
Pseudostaurosira didymum	-0.274	-0.685	-0.715	0.620
Pseudostaurosira helveticum	0.234	-0.400	-0.230	-0.137
Pseudostaurosira levanderi	0.599	-0.388	-0.161	-0.141
Pseudostaurosira marginulatum	2.033	-1.195	1.331	-0.301
Pseudostaurosira subatomoides	0.378	0.525	0.130	0.283
Pseudostaurosira rechtensis	-1.010	-0.095	0.428	-0.464
Pseudostaurosira pseudoconstruen	-1.130	-0.058	0.457	-0.366
Rossthidium pusillum	-0.370	-0.497	-0.296	-0.135
Sellaphora miniscula	-0.517	-0.367	-0.143	0.250
Sellaphora pupula	-0.120	0.274	0.724	0.261
Sellaphora laevissima	-0.288	0.699	1.365	0.362
Staurosirella oldenburgiana	-0.554	0.205	0.694	0.293
Tabellaria flocculosa	-0.266	-0.685	-0.713	0.593
Pinnularia interrupta	-0.488	-0.486	-0.316	0.174
Fragelaria elliptica	-1.375	0.167	0.889	-0.970
Pseudostaurosira parasitica	-0.392	-0.417	-0.180	-0.771
Eolimna submuralis	-0.771	-0.325	-0.029	0.114
Nitzschia inconspicua	-1.375	0.163	0.888	-0.971