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Climate-Induced Shifts in Alpine Diatom Communities: Linking Neoecological and Paleoecological Approaches to Incorporate Responses to Trophic Forcing

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Principal Investigator: Saros, Jasmine .
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Saros, Jasmine - Principal Investigator
Title:
Climate-Induced Shifts in Alpine Diatom Communities: Linking Neoecological and Paleoecological Approaches to Incorporate Responses to Trophic Forcing

Project Participants

Senior Personnel

Name: Saros, Jasmine
Worked for more than 160 Hours: Yes
Contribution to Project:
Saros is 1) Supervising all components of research; 2) Conducting field collections & laboratory experiments; 3) Supervising 1 M.S. thesis project on mesocosms & 4 undergraduate projects: 1 in lab experiments, 2 in comparative sampling, and 1 in mesocosms

Name: Pederson, Greg
Worked for more than 160 Hours: Yes
Contribution to Project:
Greg will be assisting Lisa Graumlich with the tree ring collections and analyses on this project.

Post-doc

Name: Kissman, Carrie
Worked for more than 160 Hours: Yes
Contribution to Project:
Carrie is conducting experiments designed to assess trophic forcing of sedimentary diatom signals.

Graduate Student

Name: Rose, Kevin
Worked for more than 160 Hours: Yes
Contribution to Project:
Kevin is a Ph.D. student on this project. During the summer of 2007, he is conducting experiments on the photobleaching of dissolved organic material (DOM) from different alpine lakes and working on concentrating DOM for the mesocosm experiments next summer. The mesocosm experiments will form the basis of his dissertation research.

Name: Wilcox, Erin
Worked for more than 160 Hours: Yes
Contribution to Project:
Erin is a Master's student on this project. During the summer of 2007, she is conducting resource physiology experiments with various Cyclotella species. Next summer, she will be conducting the mesocosm experiments.

Name: Slemmons, Krista
Worked for more than 160 Hours: Yes
Contribution to Project:
Krista is conducting her dissertation research on the effects of glacial meltwater on high-elevation lakes as part of this project. She has received partial summer salary from this project, and a portion of her research expenses (travel for fieldwork, supplies) have been paid by this grant.

Undergraduate Student

Name: Lucas, Chelsea

Worked for more than 160 Hours: Yes

Contribution to Project:

Chelsea is an undergraduate student who is conducting compataive lake sampling on this project. She will use the data from this sampling to construct population growth models for selected diatom taxa in these lakes.

Name: Gray, William

Worked for more than 160 Hours: Yes

Contribution to Project:

William is an undergraduate who is studying the distribution of Cyclotella taxa across alpine lakes by collecting surface sediment samples from 20 lakes in the area.

Name: Collado, Marcus

Worked for more than 160 Hours: Yes

Contribution to Project:

Marcus assisted with slide preparations and data entry during 2007-08. He will be conducting an independent research project on this grant during the summer of 2008.

Technician, Programmer

Name: Rowland, Erika

Worked for more than 160 Hours: Yes

Contribution to Project:

Erika is assisting with tree ring chronologies.

Other Participant

Name: Williamson, Craig

Worked for more than 160 Hours: Yes

Contribution to Project:

Williamson is 1) Responsible for zooplankton component of comparative sampling & Emerald mesocosm; 2) Supervising 1 Ph.D. student and 3 undergraduate projects on zooplankton and UV in the surveys and the mesocosms

Name: Stone, Jeffery

Worked for more than 160 Hours: Yes

Contribution to Project:

Stone is 1) Responsible for paleolimnology section, including coring & diatom analysis as well as overseeing additional proxies; 2) Conducting northern Rocky lake sampling with Saros & students; 3) Supervising 1 undergraduate on sediment core analyses

Name: Graumlich, Lisa

Worked for more than 160 Hours: Yes

Contribution to Project:

Graumlich is 1) Conducting tree ring reconstructions in both field sites; 2) Supervising 1 undergraduate student and 1 research associate

Research Experience for Undergraduates

Organizational Partners

US Geological Survey

Dave Clow and Cory Stephens, both with the USGS in Colorado, collaborated with us on the glacial meltwater studies. In particular, Cory Stephens assisted with GIS analyses of land class coverage by 21 land classes on about 20 watersheds.

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

Three graduate and five undergraduate students have worked on this project, with some portion of their salaries paid from this grant. This project also provided additional research experience to a post-doctoral associate, Jeffery Stone, and contributed to senior personnel Greg Pederson's PhD work, which was completed in June 2010. A high school teacher also participated in the research activities during the summer of 2009, and participated in the publication of her results in a peer-reviewed journal. One additional undergraduate in the Graumlich lab has assisted with this project, although she is funded by a different project.

Outreach Activities:

The research activities on this grant in the Saros lab are highlighted in an article in the University of Maine's research magazine, UMaine Today (http://www.umaine.edu/magazine/past-issues/volume-9-issue-4/decoding-diatoms/). Saros and Williamson also delivered talks at Yellowstone National Park's science conference for park managers in the fall of 2010. Pederson also delivered two talks at the Institute for Journalism & Natural Resources Energy Country Expedition, which aims to improve public understanding of natural resource issues. We are currently working with staff at Glacier National Park to develop interpretive materials for our research at Hidden Lake in the park.

Journal Publications

Williamson, C.E., Saros, J.E. & D.W. Schindler, "Sentinels of change", Science, p. 887, vol. 323, (2009). Published,

Saros, J.E., "Integrating neo- and paleolimnological approaches to refine interpretation of environmental change", Journal of Paleolimnology, p. 243, vol. 42, (2009). Published,

Winn, N., Williamson, C.E., Abbitt, R., Rose, K., Renwick, W., Henry, M. & J.E. Saros, "Modeling dissolved organic carbon (DOC) in subalpine and alpine lakes with GIS and remote sensing", Landscape Ecology, p. 807, vol. 24, (2009). Published,

Rose, K.C., Williamson, C.E., Saros, J.E., Sommaruga, R. & J.M. Fischer, "Differences in UV transparency and thermal structure between alpine and subalpine lakes: implications for organisms", Photochemical and Photobiological Sciences, p. 1244, vol. 8, (2009). Published,

Kessler, K., Lockwood, R.S., Williamson, C.E. & J.E. Saros, "Vertical distribution of zooplankton in subalpine and alpine lakes: Ultraviolet radiation, fish predation and the transparency-gradient hypothesis", Limnology & Oceanography, p. 2374, vol. 53, (2008). Published,

Peters, S.C., Lockwood, R., Williamson, C.E. & J.E. Saros, "Using elemental ratios of calcium and strontium to track calcium availability in the freshwater zooplankton Daphnia pulicaria", Journal of Geophysical Research-Biogeosciences, p. , vol. 113, (2008). Published, 10.1029/2008JG000782

Jasmine E. Saros, Kevin C. Rose, David W. Clow, Verlin C. Stephens, Andrea B. Nurse, Heather A. Arnett, Jeffery R. Stone, Alexander P. Wolfe and Craig E. Williamson, "Melting alpine glaciers enrich high-elevation lakes with reactive nitrogen", Environmental Science & Technology, p. 4891, vol. 44, (2010). Published,

Saros, J.E., Clow, D.W., Blett, T. and A.P. Wolfe, "Critical Nitrogen Deposition Loads in High-Elevation Lakes of the Western U.S. Inferred from Paleolimnological Records", Water, Air, and Soil Pollution, p. , vol. , (2010). Published, 10.1007/s11270-010-0526-6

Williamson, C.E., Saros, J.E., Vincent, W. and Smol, J.P., "Lakes and reservoirs as sentinels, integrators, and regulators of climate change", Limnology & Oceanography, p. 2273, vol. 54, (2009). Published,

Fischer, JM; Olson, MH; Williamson, CE; Everhart, JC; Hogan, PJ; Mack, JA; Rose, KC; Saros, JE; Stone, JR; Vinebrooke, RD, "Implications of climate change for Daphnia in alpine lakes: predictions from long-term dynamics, spatial distribution, and a short-term experiment", HYDROBIOLOGIA, p. 263, vol. 676, (2011). Published, 10.1007/s10750-011-0888-

Pederson, GT; Gray, ST; Woodhouse, CA; Betancourt, JL; Fagre, DB; Littell, JS; Watson, E; Luckman, BH; Graumlich, LJ, "The Unusual Nature of Recent Snowpack Declines in the North American Cordillera", SCIENCE, p. 332, vol. 333, (2011). Published, 10.1126/science.120157

Holtgrieve, GW; Schindler, DE; Hobbs, WO; Leavitt, PR; Ward, EJ; Bunting, L; Chen, GJ; Finney, BP; Gregory-Eaves, I; Holmgren, S; Lisac, MJ; Lisi, PJ; Nydick, K; Rogers, LA; Saros, JE; Selbie, DT; Shapley, MD; Walsh, PB; Wolfe, AP, "A Coherent Signature of Anthropogenic Nitrogen Deposition to Remote Watersheds of the Northern Hemisphere", SCIENCE, p. 1545, vol. 334, (2011). Published, 10.1126/science.121226

Arnett, H.A., Saros, J.E. & Mast, M.A., "A caveat regarding diatom-inferred nitrogen concentrations in oligotrophic lakes", Journal of Paleolimnology, p. 277, vol. 47, (2012). Published,

Saros, J.E., Stone, J.R., Pederson, G., Slemmons, K.E.H., Spanbauer, T., Schliep, A., Cahl, D., Williamson, C.E. & D.E. Engstrom, "Climate-induced changes in lake ecosystem structure inferred from coupled neo- and paleo-ecological approaches", Ecology, p. , vol. , (2012). Submitted,

Slemmons, K.E.H. & J.E. Saros, "Release of reactive nitrogen by melting alpine glaciers: Implications for phytoplankton diversity and productivity in alpine lakes", Limnology & Oceanography, p. , vol. , (2012). Submitted,

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

Our research has contributed several novel results to the field of aquatic sciences. The central goals of the project have allowed us to decipher the ecology of key Cyclotella taxa that have been changing in sediment records all over the world. Our work has helped to clarify the drivers of change in the relative abundances of these species, and provided improved mechanistic information on climate-driven change in lake ecosystems.

In addition, we have developed new optical tools for assessing allocthony in lake ecosystems. We have developed a predictive model for dissolved organic carbon concentrations in high-elevation lakes based on landscape features. We have discovered a link between melting alpine glaciers and the nitrogen chemistry of alpine lakes. Our work with deuterium isotopes is enhancing our understanding of food web dynamics in high-elevation lakes.

Our tree ring work has also contributed to the first systematic effort to produce multi-scale reconstructions of snowpack for key watersheds in the North American Cordillera.

Contributions to Other Disciplines:

In the broader context of paleoecology and climate change sciences, the integrative nature of this study has demonstrated the strength in

combining neo- and paleoecological data (as well as multiple proxies in paleoecological studies) to clarify the response of ecosystems to climate change over time scales ranging from centuries to millenia.

Contributions to Human Resource Development:

This project has funded the training of five undergraduates, three graduate students, a postdoctoral associate, and a high school teacher, all in a highly interdisciplinary approach to addressing questions of the impact of climate change on alpine ecosystems. It has also catalyzed collaborations among the mid- and early-career senior personnel involved in this project, that are continuing beyond this project.

Six of the students and post-doctoral researchers on this project are from underrepresented groups in science disciplines.

Contributions to Resources for Research and Education:

Funding from this grant provided new equipment, including an inverted microscope and profiling radiometer, to the University of Maine Diatom Ecology Laboratory. Maine is an EPSCoR state with limited resources for infrastructure, so these funds provided valuable support to expand capacity in this area. This equipment provides training for both graduate and undergraduate aquatic sciences students.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Any Book

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference

Findings

These results are either published (see list of publications), submitted, or in preparation.

A) One of our key results was advancing and clarifying our understanding of *Cyclotella* sensu lato species, which are widely distributed but poorly understood. Overall, we found that *Cyclotella* sensu lato taxa are good indicators of climate-induced changes in lake mixing patterns, but only when nutrients are sufficient. Specifically, we found:

Discostella stelligera: A synergistic interaction between nutrients and mixing depth, with this species dominating diatom assemblages in lakes with shallow mixing depths (<5 m) and moderate to high nitrate.

Cyclotella comensis: This species dominated in lakes with moderate mixing depths (>5 m) and moderate to high nitrate.

Puncticulata bodanica v. lemanica: This species dominated in lakes with deeper mixing depths (optimum of 14 m), and variable nutrient levels.

Using comparative lake sampling, we developed an inference model for mixing depths based on the relative abundances of these three diatom taxa, and applied it to the sedimentary diatom profile from an alpine lake and a boreal lake. The alpine lake reconstructions were compared with our tree ring climate inferences. Thermal reconstructions from both lakes were consistent with expected changes, with shallower mixing depths inferred for an alpine lake where treeline has advanced (Fig. 1) and deeper mixing depths inferred for a boreal lake where wind strength has increased. The inference model developed here provides a new tool to expand and refine understanding of climate-induced changes in lake ecosystems.

These results are currently under revised review at *Ecology*:
Saros, J.E., Stone, J.R., Pederson, G., Slemmons, K.E.H., Spanbauer, T., Schliep, A., Cahl, D., Williamson, C.E. and D.R. Engstrom. Climate-Induced Changes in Lake Ecosystem Structure Inferred from Coupled Neo- and Paleo-ecological Approaches.

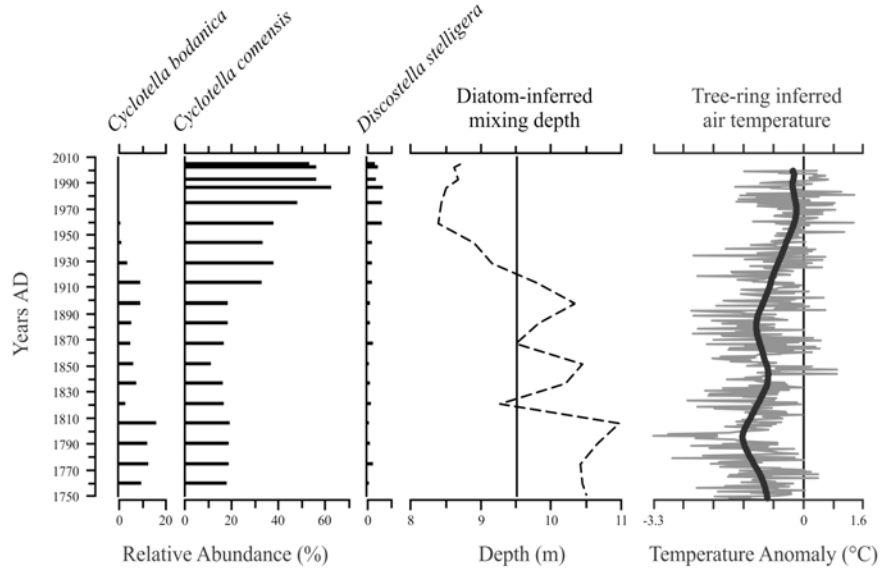

Fig. 1. Sedimentary diatom profile and reconstructed lake mixing depths for an alpine lake, compared to tree-ring inferred air temperatures.

B) With the model that we developed to infer lake mixing depths, we reconstructed changes in lake thermal structure over the late Holocene in three additional lakes located in the US Rocky Mountains. We found coherent trends in the inferred depth of the upper mixed layer, in both timing and direction (Fig. 2), suggesting major changes in lake mixing driven by large-scale teleconnective climate forcing. The inferred transitions in the thermal structure are interpreted as responses to shifts in the intensity and position of the Aleutian Low, which has a profound influence on the routing of storms in northwestern North America. Between 3.2 and 1.4 ka, a persistently weakened, westward shift in the Aleutian Low occurred. This shift resulted in an increased frequency of storm tracks across the Pacific Northwest during winter and spring. The resulting increase in precipitation and wind stress facilitated deeper mixing in all three lakes. The use of this model is advancing our ability to decipher climate-induced changes across lake ecosystems.

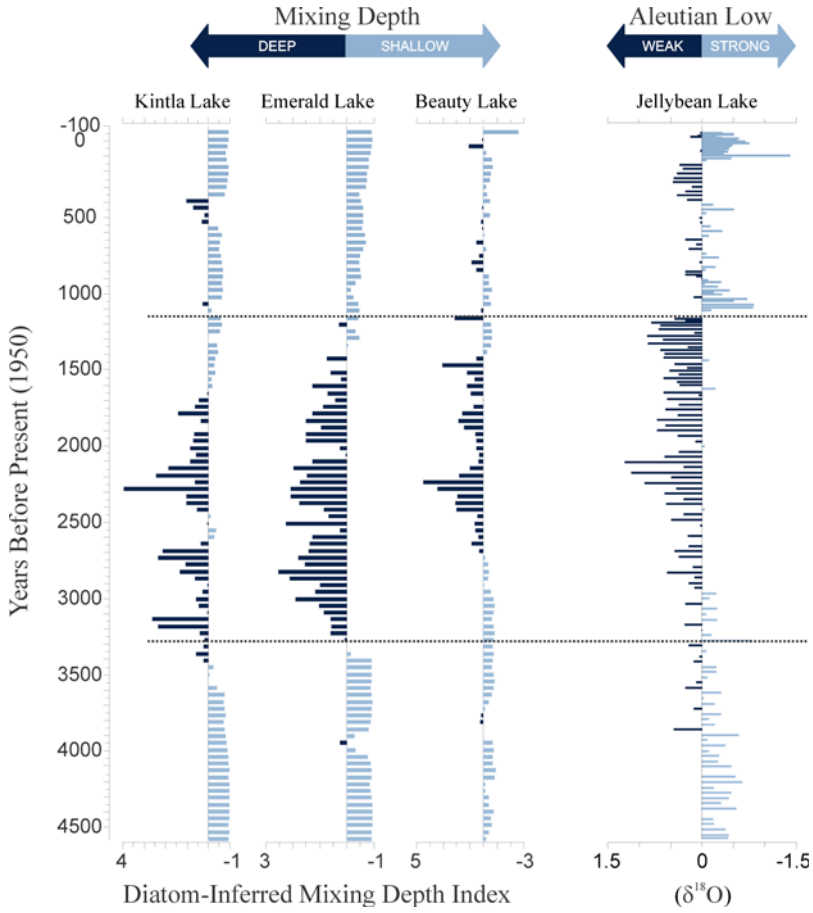

Fig. 2. Mixing Depth Indices (MDI) for Emerald, Beauty, and Kintla lakes plotted as standardized values plotted along with the $\delta^{18}O$ anomaly for Jellybean Lake.

C) Our tree ring work contributed to the first systematic effort to produce multi-scale reconstructions of snowpack for key watersheds in the North American Cordillera. Tree rings have a long history of use in reconstructing precipitation, drought, streamflow, and temperature, and successful tree-ring reconstructions of snowpack have been generated for a small number of watersheds within the Upper Colorado River basin. Pederson and Graumlich used a network of tree-ring chronologies (spanning the last 500-1000+ years) to produce millennial-length snowpack reconstructions for key headwaters in the North American Cordillera. Study watersheds correspond with U.S. Geological Survey level-6 hydrologic units (HUCs), and therefore provide information on patterns and processes across the spatial and temporal scales most relevant to water and natural resource management. Results confirm that snowpack was unusually low in the Columbia and Missouri River headwaters for much of the 20th century, and over the entire cordillera region since the 1980s. Such coherent and persistent snowpack declines are rare in the reconstructions (Fig. 3); before the 1950s the region exhibits substantial inter-basin variability with northern areas tending toward wetness when the south was dry, and vice-versa. If diminished snowpack becomes the norm, as predicted, these trends may herald a fundamental shift in regional snowpack hydrology and water availability in western North America. This change will require careful reconsideration of water planning across western North America.

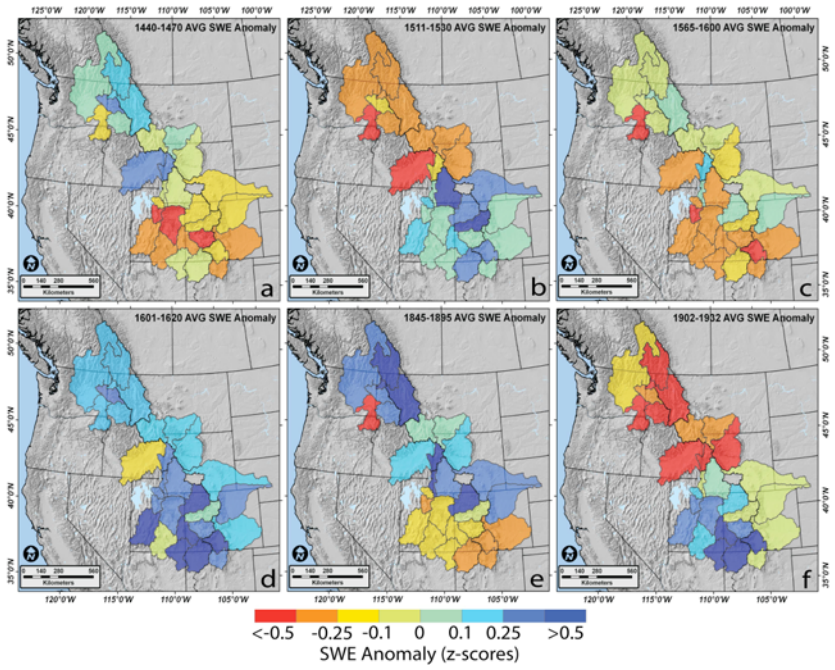

Fig. 3. Decadal departures in reconstructed April 1 SWE shown for watersheds predominately within the U.S. portion of the American Cordillera. Maps show average SWE conditions over the following intervals previously highlighted in Fig 1: a) 1440-1470, b) 1511-1530, c) 1565-1600, d) 1601-1620, e) 1845-1895, and f) 1902-1932. From Pederson et al. *Science* 2011).

D) Our experiments with both dissolved organic material (DOM) and zooplankton grazers in an alpine lake were used to assess whether trophic forcing of diatom communities could affect diatom sediment records. Our results demonstrated that the effects of DOM on pelagic ecosystems may involve more food web stimulation by nutrients rather than by fixed carbon. They also indicated that indirect effects through trophic forcing may occur even in the absence of selective impacts on consumer community structure. Given the dominance of diatoms in our study lakes as well as other lakes, these results may also have important implications for the interpretation of climate-related responses of diatoms in paleolimnological records.

E) Our experimental work also allowed us to examine the effects of climate-driven changes in terrestrially-derived DOM on consumer biomass, and the effects of DOM and zooplankton consumers on producer biomass in the warmer surface mixed stratum and the cooler, deeper, darker stratum of an alpine lake. In the absence of DOM additions consumer: producer biomass ratios showed strong increases, indicating substantial increases in consumer control. In contrast, DOM additions resulted in more stable consumer: producer biomass ratios due to a balance between DOM stimulation of both producers and consumers. DOM additions led to less strongly inverted trophic pyramids of biomass and a reduction in consumer control. Consumer biomass was greater in the warmer mixed stratum than in the colder deeper stratum in the presence and absence of DOM, while producer biomass did not differ between the two strata. Producers were nutrient limited rather than temperature or light limited, and responded strongly to DOM additions in both strata. These patterns suggest that in alpine lakes consumers are more susceptible to temperature limitation independent of nutrient supply, while producers are more susceptible to nutrient limitation. These results have important implications for assessing the dual consequences of the direct, temperature-driven vs. indirect, DOM-nutrient-driven effects of climate change on lake food webs. By altering consumer vs. resource control, direct and indirect effects of climate change may have strongly contrasting effects on the structure and function of alpine lake ecosystems. The response to DOM also suggests that lakes act as sentinels to provide signals of climate change in upstream terrestrial ecosystems.

F) We also found that glacial meltwater enriches lake ecosystems with dissolved inorganic nitrogen. We compared nutrient concentrations, transparency gradients, algal biomass, and fossil diatom species richness in two sets of high-elevation lakes: those fed by snowpack melt alone (SF lakes) and those fed by both glacial and snowpack meltwaters (GSF lakes). We found that nitrate (NO_3) concentrations in the GSF lakes were one to two orders of magnitude higher than in SF lakes. Although nitrogen (N) limitation is common in alpine lakes, algal biomass was lower in highly N-enriched GSF lakes than in the N-poor SF lakes. Contrary to expectations, GSF lakes were more transparent than SF lakes to ultraviolet and equally transparent to photosynthetically active radiation. Sediment diatom assemblages had lower taxonomic richness in the GSF lakes, a feature that has persisted over the last century. Our results demonstrated that the presence of glaciers on alpine watersheds more strongly influences NO_3^- concentrations in high-elevation lake ecosystems than any other geomorphic or biogeographic characteristic.

As mentioned in the Activities section, this finding has a number of interesting aspects to it, but we have found it to be particularly useful in clarifying our thinking about diatom distribution

patterns, as well as the types of lakes that provide the best information for climate reconstructions. This contributed to Findings A and B above.

G) Additional research activities in the field resulted in the development of new indices of environmental change based on UV and spectral slope ratios (Rose et al. 2009) as well as predictive models of dissolved organic carbon concentrations in relation to landscape features (Winn et al. 2009). A Miami-supported postdoctoral fellow working on this project carried out analyses of zooplankton allochthony using novel stable isotope techniques involving deuterium and demonstrated that zooplankton taxa differ in the extent of their allochthony in a manner consistent with what has been previously demonstrated with stable isotopes of carbon. A manuscript is in preparation from this research.

Overview
The goal of this work is to decipher the mechanisms by which climate change has altered diatom community structure in the central and northern Rocky Mountains. To achieve this goal, paleoecological analyses are being coupled with experimental and comparative approaches.

Paleoecological activities
Sedimentary diatom profiles spanning the Holocene were collected from three lakes in the central Rockies and two lakes in the northern Rockies. These cores have now been dated, and the diatoms have been counted in all of them. Zooplankton remains, total organic carbon, and biogenic silica were quantified in two key cores.

Collections and field reconnaissance of additional tree-ring chronologies for the Glacier National Park and Beartooth Mountains began in 2007 and were completed in 2008. The 2007 tree-ring collections for Glacier National Park region resulted in the addition of two new 500+ year high-elevation subalpine larch (*Larix lyallii*) chronologies. The climate-growth relationship in these chronologies showed a strong relationship with winter snowpack through an integrated response to winter precipitation and spring temperatures. These datasets entered into our published regional reconstructions of snowpack (*Science* 2011). Years of prior work in the region provide a high-density (9 chronologies) of 300 to 1000 year summer and winter moisture sensitive Douglas-fir (*Pseudotsuga menziesii*) and limber pine (*Pinus flexilis*) chronologies, so no additional precipitation sensitive collections were made.

Within the Beartooth Mountain region, however, both precipitation and temperature sensitive chronologies were located and sampled. Collections in 2008 included three temperature sensitive Engelmann spruce (*Picea engelmannii*), chronologies, one from within one diatom lake basin and the others within the broader watershed, and two additional precipitation sensitive Douglas-fir chronology. As expected, all of these sites generated 400+ year chronologies. The Douglas-fir chronologies contributed winter precipitation information to the published snowpack reconstructions, and also entered as significant predictors in streamflow reconstructions on the Bighorn River and its tributaries. The Bighorn River streamflow reconstructions are now published in a M.S. thesis by Bryan Swindell and are progressing toward publication in a scientific journal. Though the spruce chronologies contained a significant growing season temperature signal, they failed to yield a quality temperature reconstruction for the region when taken alone. The temperature sensitive chronologies were contributed to the Past Global Changes (PAGES) North American 2k initiative in an effort to improve North American temperature field reconstructions over the last 2000 years. The final winter precipitation and snowpack sensitive chronologies from both regions form the basis of a publication in *Science* (Pederson et al. 2011), and all published datasets have been archived at NOAA paleoclimatology and the International Tree-Ring Database (http://www.ncdc.noaa.gov/paleo/pubs/pederson2011/pederson2011.html). The 20th century climate database along with the tree-ring reconstructions of climate are currently being used for multi-proxy comparisons.

Experiments
Preliminary laboratory studies were conducted in 2007 and 2008 to assess grazing rates and sedimentation of phytoplankton taxa by copepod and cladoceran grazers.

Small-scale experiments were conducted in 2007 with one *Cyclotella* species to assess resource requirements and grazing rates upon this species. The modern distribution patterns of various Cyclotella taxa and zooplankton across both areas of the Rockies were investigated in 2007 as well.

During the summer of 2008, we conducted an extensive, 3-week experiment in which dissolved organic material, grazers, and incubation depth were manipulated in a factorial design to simulate changes under varying moisture balance in the region. Side experiments focused on teasing apart the nutrient enrichment versus light shading effects of dissolved organic material, as well as quantifying grazing rates on each phytoplankton species by zooplankton.

Experiments during 2009 focused on quantifying growth and grazing rates on additional key diatom taxa. We manipulated nutrients, incubation depth, and grazers in a factorial design for diatom assemblages from two lakes that contained the key diatoms of interest. These experiments have yielded the most interesting results on diatom ecology to date, and are described in the Findings section.

Sampling of Regional Lakes
Concurrent with experiments, data was collected on lakes in the Beartooth Lakes region as well as in Glacier National Park. Data collected included transparency data (305, 320, 380nm UV and PAR, 400-700 nm) and other optical parameter data including fluorescence, dissolved absorbance, dissolved organic carbon concentration, and chlorophyll concentration. Samples collected from regional lakes were analyzed in both 2008 and 2009. This data set will be combined with data from other regions to complete a large scale analysis of how variation in DOM source regulates transparency in high elevation lakes.

Patterns among the optical parameters collected in 2008 revealed that there may be relationships between traditional measures of allochthony (i.e. fluorescence) and other optical parameters. Using these observations allowed us to conduct adaptive sampling in 2009 to collect data on a broader allochthony range of lakes as well as to collect deuterium data to compare to other indices of allochthony.

Over the course of the project, as we sampled lakes to determine diatom distribution patterns, we made an unexpected discovery about the effects of glacial meltwater on high elevation lakes. We found that glacially-fed lakes are highly enriched in nitrate compared to snowmelt-fed lakes (Saros et al. 2010). While this result has a number of interesting aspects to it, we have found this observation to be particularly useful in clarifying our thinking about diatom distribution patterns, as well as the types of lakes that provide the best information for climate reconstructions. This is described in further detail in the Findings section.

Presentations of this research (64 total with NSF funding of this project acknowledged)

Pederson, G.T. 2012. (Invited) The changing snow and water resources of the Rio Grande watershed. Presented at New Mexico State Universities' (EPSCoR funded) Acequia Water Resources Research Workshop Connecting Communities: Engaging stakeholders in research. February 2-5, 2012, Synergia Ranch, Santa Fe, New Mexico.

Pederson, G.T. 2012. (Invited) The Greater Yellowstone Regions changing snowpack and water resources. Presented at Yellowstone National Park's winter speaker series. January 27, 2012, West Yellowstone Visitor Center, WY.

Saros, J.E. & K.E.H. Slemmons. 2011. Nitrogen enrichment alters the structure and function of alpine lakes. American Geophysical Union annual conference, San Francisco, USA. Poster presentation.

Stone, J.R. & J.E. Saros. 2011. Coherent shifts in Holocene climate and thermal lake structure reconstructed from fossil diatom assemblages. Geological Society of America annual meeting, Minneapolis, USA. Poster presentation.

Rose, K.C., C.E. Williamson, J.E. Saros, and C.E.H. Kissman. 2011. Indicators of Allochthony: New Tools and Techniques. 96th Annual meeting of the Ecological Society of America. August 7-12, 2011, Austin, Texas.

Invited Seminar: Williamson, C.E. 2011. Ultraviolet radiation in Lakes: Consequences of the invisible. Uppsala University Evolutionary Biology Center, September 21, 2011.

Williamson, C.E. and J.M. Fischer. 2011. Key Sentinel Responses of *Daphnia* to Climate Change: Establishing a Continental Scale Lake Observatory. IXth International Symposium on Cladocera, Verbania, Italy, October 2-8, 2011.

Invited Talk: Williamson, C.E. and J.E. Saros. 2011. Lakes as Sentinels of Climate Change: A new GLEON Initiative. 13th Meeting of the Global Lake Ecological Observatory Network, Lake Sunapee, NH. October 10-13, 2011.

Brentrup, J.A., K.C. Rose, T.H. Leach, C.E. Williamson, J.M. Fischer, J.E. Saros, B.R. Hargreaves, R.E. Moeller. 2011. Sentinel Responses to Extreme Precipitation Events in Lakes: Changes in UV Transparency. 13th Meeting of the Global Lake Ecological Observatory Network, Lake Sunapee, NH. October 10-13, 2011.

Rose, K.C. J. Read, C. McBride, C.E Williamson, and D. Hamilton. 2011. Deep Chlorophyll Maxima: Where do they form and what implications do they have for ecosystem structure and metabolism estimates? 13th Meeting of the Global Lake Ecological Observatory Network, Lake Sunapee, NH. October 10-13, 2011.

Invited Lecture: Ultraviolet radiation in lakes: Consequences of the invisible. Institute of Ecology, University of Innsbruck, Innsbruck, Austria. October 24, 2011.

Invited Seminar: Ultraviolet radiation in lakes: Consequences of the invisible. Institute of Ecology, University of Innsbruck, Innsbruck, Austria. October 24, 2011.

Invited Seminar: Williamson, C.E. 2011. Lakes as sensors in the landscape: Consequences of the invisible. National Ecological Observatory Network (NEON), Boulder, Colorado. November 16, 2011.

Pederson, G.T. 2011. A millennium of snowpack variability and change in the North American Cordillera: contextualizing recent and projected changes. Presented at the 2011 American Fisheries Society's 141 Annual Meeting. September 4-8, Seattle, WA.

Pederson, G.T., S.T. Gray, C.A. Woodhouse, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, & L.J. Graumlich, 2011. Long-term snowpack variability and change in the North American Cordillera. Presented at the 2011 UCOR/NIWR Annual Conference, Planning for Tomorrow's Water: Snowpack, Aquifers, and Reservoirs. July 11-14, Boulder Colorado.

Pederson, G.T. 2011. A millennium of snowpack and glacier change in Western North America. Presented at USGS, Northern Rocky Mountain Science center Ecolunch Seminar Series. June 28, 2011, Bozeman, MT.

Pederson, G.T. 2011. A millennium of snowpack and glacier change in Western North America: Contextualizing recent and projected changes. Presented at a GNLCC webinar. June 1, 2011, Bozeman, MT.

Pederson, G.T. 2011. A millennium of snowpack and glacier change in Western North America: Contextualizing recent and projected changes. Presented at a USFS Natural Resources and Climate Change Workshop, April 29, 2011, Cody, WY.

Pederson, G.T., S.T. Gray, C.A. Woodhouse, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, & L.J. Graumlich, 2011. A millennium of snowpack variability and change in the North American Cordillera. Presented at the Association of American Geographers (AAG) 2011 Annual Meeting, May 12, 2011, Seattle, WA.

Pederson, G.T., S.T. Gray, C.A. Woodhouse, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, & L.J. Graumlich, 2011. A millennium of snowpack variability and change in the North American Cordillera. Presented at the Inter Americas Institute Climate Research Network (IAI CRN 2047) science synthesis and planning meeting Documenting, understanding and projecting changes in the hydrological cycle in the American Cordillera, April 3-9, 2011, Tilicara, Argentina.

Pederson, G.T. 2011. Long-term snowpack variability and change in the North American Cordillera. Presented at the 2011 Pacific Climate Workshop (PACLIM), March 6-9, 2011, Asilomar State Conference Grounds, Pacific Grove, CA.

Pederson, G.T. 2011. (Invited) A millennium of snowpack variability and change in the North American Cordillera: contextualizing recent and projected changes. Presented at the 2011 American Fisheries Society's 141 Annual Meeting. September 4-8, Seattle, WA.

Pederson, G.T. 2011. (Invited) The dendroclimatic potential for North American field reconstructions of snowpack and temperature. Presented at the PAGES North American 2k Working Group Meeting. September 27-28, Tucson, AZ.

Pederson, G.T. 2011. (Invited) A Changing Western North American Hydroclimate: Earlier spring onset and the unusual nature of recent snowpack declines. Presented at Montana State University Earth Science Departmental Seminar Series. October 11, 2011, Bozeman, MT.

Pederson, G.T. 2011. (Invited) A Changing Western North American Hydroclimate: Earlier spring onset and the unusual nature of recent snowpack declines. Presented at the 2011 Institute for Journalism & Natural Resources Energy Country Expedition. November 11, 2011, Villas Caldera Science & Education Center, Jemez Springs, New Mexico.

Pederson, G.T. 2011. (Invited) Global climate change fundamentals: The underpinnings of climate change research. Presented at the 2011 Institute for Journalism & Natural Resources Energy Country Expedition. November 11, 2011, Villas Caldera Science & Education Center, Jemez Springs, New Mexico.

Tucker, A., C.E. Williamson, J.T. Oris, A. Gevertz, and M. Olson. 2010. Water temperature and ultraviolet radiation transparency interact to control invasive warm-water fish establishment in a cold, clear, high-elevation lake. Poster presentation at the 10th Biennial Scientific Conference on the Greater Yellowstone Ecosystem, October 13, 2010.

Williamson, C.E., K.C. Rose, J. Mack, J.E. Saros, J.M. Fischer, J. Everhart, and M. Winder. 2010. Water transparency to UV radiation as a sentinel of climate and land-use-driven changes in the terrestrial landscape: Potential consequences for zooplankton and invasive invertebrates. 10th Biennial Scientific Conference on the Greater Yellowstone Ecosystem, October 13, 2010.

Saros, J.E., Wolfe, A.P., Rose, K.C., and C.E. Williamson. 2010. Melting alpine glaciers enrich lake ecosystems in the Beartooth Mountains with reactive nitrogen and reduce biodiversity. Greater Yellowstone Ecosystem 10th Biennial Science Conference. Mammoth Hot Springs, Wyoming, USA. Oral Presentation.

Saros, J.E., Stone, J.R. & K.E.H. Slemmons. 2010. Deciphering the ecology of *Cyclotella* sensu lato taxa in oligotrophic lakes. International Diatom Symposium. St. Paul, Minnesota, USA. Oral presentation.

Stone, J.R., Saros, J.E., Spanbauer, T., Pederson, G.T. & C.E. Williamson. 2010. Coherent regional shifts in climate and lake structure reconstructed from fossil phytoplankton assemblages of four lakes in the Northern Rockies. International Diatom Symposium. St. Paul, Minnesota, USA. Oral presentation.

Williamson, C.E., Saros, J.E., Kissman, C., Rose, K.C., Fischer, J.M., and J. Everhart. 2010. Water transparency to UV radiation in mountain lakes: consequences of climate-driven changes in terrestrial inputs for light, temperature, and nutrient regulation of trophic interactions. Global Change and the World's Mountains Conference, September 26-30, 2010, Perth, Scotland. Oral Presentation.

Fischer, J.M., M.H. Olson, J.C. Everhart, K.C. Rose, C.E. Williamson, and R.D. Vinebrooke. 2010. Factors influencing the distribution of *Daphnia middendorffiana* in alpine lakes of the Canadian Rockies**.** Global Change and the World's Mountains Conference; Perth, Scotland, September 26-30, 2010.

Rose, K.C., Wiliamson, C.E., Saros, J.E., and Kissman, C.E.H. 2010. What can dissolved absorbance tell us about lake ecology? Global Lake Ecological Observatory Network (GLEON) Meeting 10, May 10-15 2010, Torres, Brazil. Oral Presentation.

Rose, K.C., Williamson, C.E., Saros, J.E., and Kissman, C.E.H. 2010. Indicators of Allochthony. American Society for Limnology and Oceanography. Santa Fe, New Mexico, USA. Poster Presentation.

Kissman, C.E.H., Williamson, C.E., Saros, J.E., and K.C. Rose. 2010. The Role of Climate Induced Trophic Forcing in Alpine Lake Ecosystems: Coupling Plankton Dynamics to Sediment Signals. American Society for Limnology and Oceanography. Santa Fe, New Mexico, USA. Poster Presentation.

Saros, J.E., Wolfe, A.P., Clow, D.W., Rose, K.C., and C.E. Williamson. 2010. Melting Alpine Glaciers Enrich Lake Ecosystems With Reactive Nitrogen and Reduce Biodiversity. American Society for Limnology and Oceanography. Santa Fe, New Mexico, USA. Oral Presentation.

Slemmons, K. and J.E. Saros. 2010. Release of reactive nitrogen by melting alpine glaciers: effects on diatom diversity in lake ecosystems over the last century. American Society for Limnology and Oceanography. Santa Fe, New Mexico, USA. Poster Presentation. **Winner of Best Student Poster Award.**

Invited Seminar: Williamson, C.E. 2010. Ultraviolet radiation: Beneficial and detrimental effects in lakes. Dartmouth College, October 8, 2010.

Williamson, C.E., J.M. Fischer, E.P. Overholt, S.M. Bollens, and J.K. Breckenridge. 2010. Shedding light on zooplankton diel vertical migration: Integration of abiotic and biotic drivers across transparency gradients. American Society of Limnology and Oceanography Summer Meeting, Santa Fe, New Mexico, June 6-11, 2010.

Invited Seminar: Williamson, C.E. 2010. "Seeing the unseen in lakes: Ultraviolet radiation, fish, and zooplankton." Ohio State University, April 8, 2010.

Pederson GT. 2010. Recent Climatic Changes Across the Western U.S.: Biophysical and Phenological Responses. USFWS LCC Seminar Series, Fish Technology Center, March 24, 2010, Bozeman, MT.

Pederson GT. 2010. Recent Climatic Changes Across the Western U.S.: Biophysical and Phenological Responses. Ecology Seminar, Montana State University, March 11, 2010, Bozeman, MT.

Invited Talk: Williamson, C.E. 2009. "Ultraviolet radiation: Climate forcing and biotic response". Cornell University Biogeochemistry IGERT Program, March 6, 2009.

Invited Talk: Williamson, C.E. 2009. "Ultraviolet radiation: Climate forcing and biotic response". Université du Québec à Trois-Rivières Research Group on Aquatic Ecosystems. April 2, 2009.

Invited Talk: Williamson, C.E. 2009. "Ultraviolet radiation: Climate forcing and biotic response". University of Maine Climate Change Institute, April 24, 2009.

Invited Talk: Williamson, C.E. 2009. “Ultraviolet radiation: Climate forcing and biotic response”. University of Lund Limnology and Department of Ecology. May 8, 2009.

Invited talk: Williamson, C.E. 2009. "How do fish and zooplankton respond to UV radiation in lakes?" Shackelton Field Station, Cornell University, June 11, 2009.

Rose, K.C. Williamson, C.E., Saros, J.E., and C. Kissman. 2009. Indicators of Allochthony in High Mountain Lakes. Global Lake Ecological Observatory Network (GLEON) Meeting 9, October 12-15, 2009, Boulder Junction, Wisconsin, USA. Poster Presentation.

Rose, K.C., C.E. Williamson, and J.E. Saros. 2009. Transparency patterns of high elevation lakes in the Beartooth Moutains, MT/WY, USA. Global Lake Ecological Observatory Network (GLEON) Meeting 8 February 2-6, 2009, Hamilton, New Zealand. Poster Presentation.

Rose, K.C., C.E. Williamson, J.E. Saros. 2008. The development of an optical indicator of allochthony in low DOM lakes. Global Lake Ecological Observatory Network (GLEON) Meeting 7, September 29-October 2, 2008, Uppsala University, Norrtalje, Sweden. Poster Presentation.

Rose, K.C., C.E. Williamson, J.E. Saros. 2008. The development of an optical indicator of allochthony in low DOM lakes. American Geophysical Union Chapman Conference on “Lakes and reservoirs as sentinels, integrators, and regulators of climate change”, Incline Village, NV. September 8-10, 2008. Poster Presentation.

Winn, N., C.E. Williamson, R. Abbitt, M. Henry, K.C. Rose, and J.E. Saros. 2008. Dissolved organic carbon prediction in the lakes of the Absaroka-Beartooth Wilderness using a GIS and remote sensing. Assoc. Amer. Geogr. Annual Meeting, Boston, MA April 15-19, 2008. Poster Presentation.

Rose, K.C., C.E. Williamson, J.E. Saros. 2008. Adding UV Transparency as an Optical Indicator of Allochthony in Low DOM Lakes. Global Lake Ecological Observatory Network (GLEON) Meeting 6, February 2-5, 2008, Lake Placid, Florida. Poster Presentation.

Williamson, C.E., and K.C. Rose. 2007. Ultraviolet transparency as an indicator of lake metabolism in the Global Lake Ecological Observatory Network. Fourth Global Lake Ecological Observatory Network (GLEON) Workshop, March 3, 2007, Lammi Biological Station, Finland. Oral Presentation, Invited Plenary Lecture.

Saros, J.E. Melting alpine glaciers enrich high-elevation lakes with reactive nitrogen. Invited seminar, Lund University, Lund, Sweden, November 2009.

Spanbauer, T.L., Stone, J.R., Saros, J.E. & S.C. Fritz. 2009. *Cyclotella* response to climate change during the Holocene: an analysis of the diatom paleoecology of a pristine alpine lake in Glacier National Park. Poster Presentation, 20th North American Diatom Symposium, Iowa Lakeside Laboratory.

Kissman, C.E.H., Winder, M., Williamson, C.E. & J.E. Saros. Deuterium stable isotopes: What do they reveal about food sources for *Diaptomus* sp. and cladocerans in alpine and subalpine lakes? Ecological Society of America annual meeting, Albuquerque, NM, August 2009.

Saros, J.E., Nurse, A., & G. Fulford. Using glacially-derived nitrogen pulses into alpine lakes ecosystems as indicators of climate change. Northeast Geological Society of America annual

meeting, Portland, ME, March 2009.

Saros, J.E. Ecological change in high-elevation lakes of the western U.S. as a consequence of sustained nitrogen deposition. Invited seminar, McGill University, Montreal, Canada, March 2009.

Saros, J.E., Williamson, C.E., & A.P. Wolfe. Response of alpine versus subalpine lakes to nitrogen deposition: similar but asynchronous community and ecosystem-level changes. American Society of Limnology and Oceanography annual meeting, Nice, France, January 2009.

Williamson, C.E., Kessler, K., Saros, J.E. & R.S. Lockwood. Vertical distribution of zooplankton in subalpine and alpine lakes: Ultraviolet radiation, fish predation, and the transparency-gradient hypothesis. American Society of Limnology and Oceanography annual meeting, Nice, France, January 2009.

Kessler, K., Lockwood, R.S., Williamson, C.E. & J.E. Saros. Vertical distribution of zooplankton in subalpine and alpine lakes: does ultraviolet radiation play a role? North American Lake Management Society annual meeting, Alberta, Canada, November 2008.

Saros, J.E. 2008. Lakes as sentinels and integrators of climate change: Identifying key mechanisms by merging experimental and paleolimnological approaches. Keynote Address, American Geophysical Union Chapman Conference "Lakes & Reservoirs as Sentinels, Integrators, and Regulators of Climate Change" (Lake Tahoe).