Environment and Natural Resources Trust Fund

Research Addendum

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PROJECT TITLE: Unprecedented Recent Changes in Minnesota's Wilderness Lakes

PROJECT NUMBER: 137-F1+2+5

1. ABSTRACT

Minnesota's remote wilderness lakes are experiencing unexpected ecological change, including blooms of noxious blue-green algae. Preliminary sediment-core data indicate that these changes are unique in the recent history of the lakes. However, land-use change and related increases in phosphorus input are not the likely cause. Rather, the lakes may be responding to a warming climate, as indicated by a lengthening of the ice-free season and stronger thermal stratification during summer. This project will explore whether there is a causal link between observed temperature increases and ecological conditions in northern Minnesota lakes, the likely physical and biological controls, and how these effects vary among different types of lakes. Specifically, this study will: (1) Reconstruct ecological change in a set of carefully-chosen experimental lakes from sediment records spanning the last 150-200 years; these records will place recent lake changes in the context of longer-term ecological conditions; (2) Compare these environmental records among four general lake types likely to represent a range of sensitivity to climate warming; specifically shallow and deep lakes and lakes with small and large surface areas; and (3) Reconstruct the thermal conditions (stratification, ice-free season, temperatures) of the study lakes based on local climate records and hydrodynamic lake models. These lake-thermal records will then be compared with ecological reconstructions from the sediment cores to develop predictive relationships between lake type and climate-induced ecological risk.

2. BACKGROUND

Ecological changes, including increases in cyanobacteria (blue-green algae), are occurring in our remote northern lakes. These changes do not fit the traditional paradigm of nutrient loading and eutrophication and may be the result of recent climate warming. Climate change has the potential to severely disrupt Minnesota's aquatic ecosystems both directly though changes in temperature and precipitation and in concert with other man-made stressors such as nutrient pollution, invasive species, and land-use change. We currently have only a limited scientific grasp of how these forces will interact or how our lakes will respond, yet predicting these effects will be critical to both resource management and public understanding of changes that have already begun.

Recent studies have documented a series of possible climate-induced changes in boreal-region lakes, including a longer ice-free season (Johnson and Stefan 2006, Jensen et al. 2007), stronger thermal stratification, increased inputs of dissolved organic carbon (Monteith et al. 2007), shifts in algal communities (Rühland et al. 2008), and most alarmingly an increased frequency of cyanobacterial blooms (Edlund et al. 2010). These changes have been noted in remote lakes far removed from direct human disturbance, with the strongest evidence coming from analysis of dated sediment cores that record the recent history of the lakes. However, the scientific picture is currently very incomplete: the observed changes vary considerably among lakes, the physical and biological controls are poorly understood, and the consequences for higher food-chain organisms are virtually unknown. With such incomplete knowledge there is the very distinct possibility that climate effects could be attributed to the wrong causes (e.g. nutrient loading), and resource-management efforts misdirected. What is needed then, is a systematic assessment of recent changes in remote Minnesota lakes where effects other than climate can be ruled out and where local factors likely to influence lake sensitivity to climate can be rigorously evaluated. Such an assessment would help reveal the ways in which climate affects lakes and would provide a framework for determining which types of lakes are most at risk of undesirable ecological shifts.

This project will reconstruct ecological change in remote lakes from northeastern Minnesota using biological fossils and chemical signatures preserved in dated sediment cores. These changes will be compared among contrasting lake types and with physical models of lake thermal conditions. Because of year-to-year variability, the effects of climate change can be discerned only over longer periods of time, making retrospective studies such as proposed here far superior to direct observations of short duration. Moreover, possible climate effects on lakes have already been noted in sediment-core studies from arctic and boreal regions (Smol et al. 2005, Rühland et al. 2008) and more locally in our recent work at Isle Royale and Voyageurs National Parks (Serieyssol et al. 2009, Edlund et al. 2010). These studies document a systematic replacement of heavily silicified diatoms (e.g. *Aulacoseira* spp.) by small centric species (e.g. *Cyclotella* spp.), a change that has been attributed to differences in sinking rates with increased stability of thermal stratification (Rühland et al. 2008). Increases in cyanobacteria blooms, reconstructed from algal pigments preserved in sediment cores, may likewise be related to lake thermal structure through direct effects of higher surface temperatures, longer and more intense stratification, and increased internal nutrient loads (Wagner and Adrian 2009).

3. Hypothesis and Questions

The basic premise of this study is that remote lakes at mid to high latitudes are showing ecological change that may be related to climate warming or other broad regional stressors. These changes, which are occurring in algal communities at the base of the aquatic food chain, have been clearly documented from lake sediment cores spanning the last century. It is our working hypothesis that these ecological shifts are tied to changes in thermal structure of the lakes including stability and depth of stratification, length of the ice-free season, surface and bottom water temperatures, and hypolimnetic oxygen conditions. These physical factors in turn affect algal communities by influencing in-lake nutrient cycling, light regime, or possibly turbulence and cell sinking rates. The study is designed to test this hypothesis by answering the following questions:

(1) Do remote, wilderness lakes in northern Minnesota show systematic shifts in ecological state during the last century as reconstructed from algal remains and geochemical signatures preserved in lake sediment records?
(2) How have thermal conditions in these lakes changed over the same time period; how does the timing and magnitude of these changes vary among lakes of differing morphometry (depth) and surface area?

(3) What is the relationship between the ecological and thermal histories of these lakes and how does that relationship vary with respect to lake size and depth?
(4) If the ecological changes show no relationship with thermal trends or lake type, can they be related to other stressors (e.g. atmospheric nitrogen deposition, fire/logging history) that would differ from climate with respect to timing, biotic effect, or lake type?

The study is thus an historic experiment in which the hypothesized changes have already occurred and will be evaluated by environmental reconstruction and correlation. We know from previous studies that both the thermal structure and ecological state of these lakes have likely changed. The question is whether these changes are related in a cause/effect manner and how lake morphometry influences sensitivity to climate forcing. These results should shed light on the likely mechanisms by which thermal structure affects algal communities (e.g. nutrients, light, turbulence). The ultimate aim is to provide a means of predicting from simple morphometric parameters the likely sensitivity of different lakes types to future climate forcing.

4. Methodology

Environmental Reconstructions

The limnological effects of climate change and other environmental stressors are difficult to assess from short term monitoring owing to year-to-year climate variability, complex environmental feedbacks, and lagged and legacy effects from prior years. Moreover, there are very few lakes anywhere that have monitoring data of more than a few decades and virtually none in remote wilderness regions such as northern Minnesota. Hence, the only way to understand long-term limnological change, including pre-disturbance reference conditions, is by paleolimnological methods that reconstruct past lake conditions from fossil and geochemical signatures preserved in dated sediment cores. In this study sediment cores will be analyzed for biotic and chemical indicators of ecological change at roughly decadal intervals over the last 150-200 years of record. The primary indicators will include (a) fossil diatoms – microscopic algae with silica cell walls that are powerful indicators of water quality; (b) biogenic silica – for assessment of total diatom productivity; (c) fossil algal pigments – chemical signatures for the past abundance of different algal groups, particularly cyanobacteria (blue-green algae); (d) isotopes of nitrogen and carbon – indicators of lake productivity and changing nitrogen inputs; and (e) sediment phosphorus – to determine past phosphorus loading to the lakes.

Lake Selection and Mapping: Sediment cores will be taken from twelve lakes located in undisturbed watersheds of the Boundary Waters Canoe Area Wilderness and surrounding Superior National Forest. Three lakes will be selected from each of four morphometry classes: (1) small ($A_L \approx 10$ ha) and shallow ($Z_{max} \approx 5$ m), (2) small and deep ($Z_{max} \approx 25$ m), (3) large ($A_L \approx 100$ ha) and shallow, and (4) large and deep. All study lakes will have small watersheds relative to their surface areas ($A_L/A_W \approx 5$) so as to minimize effects related to differences in contributing drainage areas and hydrology. Watershed vegetation, especially the percentage of wetland coverage, will also be kept as similar as possible. Lake-surface and watershed areas will be mapped by GIS methods, and depth surveys will be conducted by tandem GPS/depth-meter for those sites lacking suitable lake-depth maps. Local fire and/or logging history for each watershed will be determined from published (e.g. Heinselman 1973) and unpublished agency (USFS) records. To the extent possible, lakes in recently-burned (since c. 1900) watersheds, will be avoided so as to eliminate confounding effects of that stressor.

Core Collection and Dating: A single sediment core of 60-80 cm in length will be collected from each study lake using a piston corer equipped with a 7-cm diameter polycarbonate core barrel and operated from the lake surface by Mg-alloy drive-rods (Wright 1991). Core sites will be located by sonar and bathymetric maps in deep flat areas of the basin, distant from any steep slopes that might be subject to slumping. Cores will be extruded vertically on site at 1-2 cm increments into polypropylene collection jars. Samples will first be analyzed for dry-density (dry mass per volume of fresh sediment) and water, organic, and carbonate content by standard loss-on-ignition techniques (Heiri et al. 2001). Subsamples from each core increment will be frozen for subsequent analysis of algal pigments, and the remaining sediments will be freeze dried for all other analyses and for core archival. All cores will be dated by ^{210}Pb using alpha spectrometry methods (Eakins and Morrison 1978), with dates and sediment accumulation rates calculated according to the CRS model (Appleby 2001). Because of slow sediment accumulation rates in these northern lakes, it should be possible to obtain reliable dates back to the mid to early 1800s. Dating resolution will be roughly decadal.

Diatom Analysis: A total of fifteen increments per core will be analyzed for diatom microfossils; ten of the samples will be concentrated in the upper part of the core representing about the last 100 years (ca. 10-year resolution). The remaining five samples will be taken at core intervals representing 10-20 year resolution from pre- settlement times (pre-1900). Samples will be pre-treated with dilute HCl and 30% H_2O_2, with the cleaned residue dried onto microscope coverslips, and the coverslips mounted on microslides using Naphrax.

Diatoms and chrysophyte cysts will be identified to species level using light microscopes with full immersion optics capable of 1200X magnification at an N.A. of 1.4. A minimum of 400 valves will be counted in each sample. Abundances will be reported as percentage abundance relative to total diatom counts. Identification of diatoms will use regional floras (e.g. Patrick and Reimer 1966, 1975, Edlund 1994, Camburn and Charles 2000) and primary literature.

Stratigraphies of predominant diatoms (species greater than or equal to 5% relative abundance) will be plotted against core date. Relationships among diatom communities within a sediment core will be explored using Detrended Correspondence Analysis (DCA); analyses will be performed using the software package R (Ihaka and Gentleman 1996). Core depths/dates will be plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples. Diatom community data will be further used to determine the timing and extent of major ecological changes in each lake including shifts between benthic and planktonic dominance and shifts between diatoms and chrysophytes.

A diatom calibration set from a suite of 155 Minnesota lakes will be available for this study (Ramstack et al. 2003, Edlund and Ramstack 2006, Edlund and Ramstack unpublished data). The relationship between diatom community assemblage and measured environmental variables in the calibration set can be used to determine the primary drivers of diatom community change in the cores.

Biogenic Silica: Changes in overall lake productivity can be assessed through the selective extraction and analysis of biologic silica (bSi) derived from siliceous algae, principally diatoms and chrysophytes. Sediment bSi concentrations will be measured using a time-step digestion (DeMaster 1981, Conley and Schelske 2001). In this procedure, freeze-dried subsamples are digested in 1% Na_2CO_3 for five hours in an 85°C water-bath shaker. The solutions are sub-sampled at 3-, 4- and 5-hour time steps to chart the progressive silica dissolution over time and thereby correct for Si contributed by mineral silicates. Twenty sediment intervals will be analyzed from each core.

Carbon, Nitrogen, and Phosphorus: Total nitrogen and organic carbon will be measured on selected core intervals (20/core) by combusting the freeze-dried sediments in a Carlo-Erba NA 1500 CNS elemental analyzer. The samples will be pretreated with concentrated HCl to remove inorganic carbon prior to analysis. Total sediment phosphorus will be analyzed colorimetrically on a Lachat QuikChem 8000 Autoanalyzer following sequential peroxide/HCl digestion (Engstrom and Wright 1984). Ratios of C:N can help distinguish between organic matter of terrestrial origin (high C:N) from in-lake algal sources (low C:N) and hence changes in lake productivity (Meyers and Teranes 2001). Phosphorus accumulation in sediments provides a measure of watershed P inputs to the lake, though interpretations must take into account the potential for in-lake remobiliation as well as post-depositional diagenesis (Engstrom and Wright 1984).

Stable C and N isotopes will be quantified from freeze-dried subsamples using a Thermoquest (Finnigan-MAT) Delta Plus^{XL} mass spectrometer interfaced with a Carlo Erba NC-2500 elemental analyzer following the procedures of Savage et al. (2004). Stable nitrogen isotopes will be used to track changes in atmospheric N-deposition (Wolfe et al. 2003, Enders et al. 2008). Both wet and dry deposition of N with a depleted δ15N [ratio of 15N: 14N; as per mil (‰), relative to air (0‰)] signature from fossil fuel and fertilizer NOx emissions (including agricultural nitrification) can be assimilated by remote lake ecosystems. The resulting organic-N in the sediments can therefore reflect the changes in source N over time. Possible fractionation effects associated with aquatic production (e.g. changes in trophic enrichment; N assimilation) and post-depositional diagenesis will be considered (Peterson and Fry 1987, Gälman et al. 2009). Analysis of C isotopes will be undertaken on the same sediment sample to gain confirmation of the organic matter source and aquatic productivity (Brenner et al. 1999). Carbon and nitrogen analyses will be performed by Dr. Peter Leavitt at the University of Alberta. Dr. Leavitt will also assist in the interpretation of these proxy records.

Algal Pigments: Sedimentary pigments will be extracted, filtered and dried under N_2 gas following the procedures of Leavitt et al. (1989). Carotenoid, Chlorophyll (Chl), and pigment-derivative concentrations will be quantified using a Hewlett-Packard 1050 HPLC system following the reversed-phase procedure of Mantoura and Llewellyn (1983), as modified by Leavitt et al. (1989). Spectral characteristics, chromatographic mobility, and functional group assays will be used to identify pigments from all sources (Leavitt and Carpenter 1989). Pigment analysis will focus on carotenoids characteristic of cryptophytes (alloxanthin), diatoms, chrysophytes, and some dinoflagellates (fucoxanthin), mainly diatoms (diatoxanthin), chlorophytes and cyanobacteria (lutein-zeaxanthin), all cyanobacteria (echinenone), filamentous or colonial cyanobacteria (myxoxanthophyll, canthaxanthin), and potentially N_2-fixing cyanobacteria (aphanizophyll), as well as the major parent and derivative compounds of Chl *a*, *b*, and *c*. Pigment concentrations will be expressed as nmoles pigment g^{-1} organic matter, an index that is linearly related to algal biomass in the water column (Leavitt and Findlay 1994). Pigment analyses will also be carried out by Dr. Peter Leavitt, an internationally-recognized expert in fossil pigments analysis and interpretation.

Modeling Lake Thermal Conditions

Understanding the differences in thermal dynamics among the different lake types is central to predicting how Minnesota lakes could respond to climate changes. In addition, comparing historical changes in thermal structure to biological trends observed in the sediment cores is a key component to linking climate change to ecological change. The remote lakes necessary for this study will not have monitoring data available for thermal parameters such as ice cover, water temperature or stratification. This information, both recent and historical, will need to be generated through proven lake models.

MINLAKE96 is a deterministic, process-oriented model developed at the University of Minnesota (Fang and Stefan 1997, Stefan et al. 1998) for the purposes of simulating thermal and dissolved oxygen conditions in temperate region polymictic and dimictic lakes. The model has been successfully calibrated to Minnesota lakes and demonstrated to predict water column temperatures within 1.4 ^{o}C on a daily basis and forecast ice formation dates with 7 days of observed values. The extensive application of this model to Minnesota lakes and its demonstrated accuracy make it ideal for use in this study.

The model will be used to describe the following thermal characteristic of the 12 study lakes:

i) date of ice formation and duration of ice cover
ii) date of summer stratification and fall turnover
iii) depth of stratification
iv) presence and duration of anoxia periods

The four types of study lakes should be distinctly different in their combinations of these different parameters. By applying long-term climate/weather records to the model, an assessment of how these conditions have changed over time will be generated.

The model requires knowledge of several lake attributes as well as meteorological data. Required lake attributes are: lake surface area, maximum depth, Secchi depth, particulate concentration, and surface area to depth profiles. The first four are readily available or easily measured in the field. The surface area to depth profiles can be generated from bathymetric maps when available. Several of the smaller remote lakes are unlikely to have bathymetric data. This information will be collected using a tandem GPS-depth meter and multiple transects across a lake. Temperature and oxygen profiles will be measured on each study lake at the time of coring.

Meteorological data required for the model are: daily air temperature, wind speed and direction, solar radiation, and dew point. Over 100 years of daily air temperature data are available for several stations adjacent to the proposed study region, e.g. Ely, Bemidji and International Falls. The other parameters have limited availability, with abbreviated records extending back 40 years or less. We will generate average daily values for these parameters from the existing record and apply these estimates to the entire modeled period (~ 100 years).

Dr Heinz Stefan (University of Minnesota) and Dr Xing Fang (Auburn University) have extensive experience with the MINLAKE96 model and its application to Minnesota Lakes. They have agreed to provide consulting services to assist with running the model.

Model output will quantify present-day differences in thermal dynamics among the study lakes. Characteristics such as date of ice formation and duration of ice cover are expected to be vary considerably among the four lake types. These differences govern important eco-limnologic factors such growing season and nutrient cycling and should correlate with observed differences in biological communities among the lakes. More importantly, the model will predict if and how thermal characteristic have changed over time. The timing and magnitude of these changes will be compared with the biological changes measured in the sediment cores. The presence or absence of temporal correlations between biological and thermal trends will offer important evidence on the influence of climate change on lake ecology.

Hypothesis Testing

We will explore three broad regional stressors as potential drivers for ecological change in the study lakes. These include climate (temperature), atmospheric nitrogen deposition, and land-use disturbance (logging). A fourth possibility will be considered – that of no discernable change (the null hypothesis). We anticipate that logging effects, for those watersheds where it occurred, will appear much earlier in the sediment record than those for climate or N-deposition and thus be easily distinguished (e.g. Serieyssol et al. 2009). On the other hand, changes in climate and N-deposition are more contemporaneous and resulting effects more likely to be confounded in the sediment record. The study design, involving multiple and contrasting lake types and multiple and complementary proxy data should help disentangle these two drivers of lake change. Table 1 summarizes predicted changes in sedimentary records resulting from climate warming and N-deposition.

Table 1. Predicted changes in sediment proxies from climate warming and atmospheric nitrogen deposition

	Climate warming	N-deposition
Timing	Dependent on lake morphometry class	Synchronous or no relation to lake morphometry
Correlation	With modeled lake thermal hindcasts	With N-deposition trends from NADP sites
Diatoms	Change from heavily silicified *Aulacoseira* to small *Cyclotella* species	Increase in N-responsive *Fragilaria* and *Asterionella* species
Algal Pigments	Increase in cyanobacterial pigments; possible increase in N-fixers	No increase in cyanobacteria; possible decrease in N-fixers
N-isotopes	Possible indirect effects (+\-) from changes in algal composition	Decrease in ^{15}N from relaxation of N limitation
Biogenic Si	Possible decrease from competition with increasing cyanobacteria	Increase from greater diatom productivity
Sediment P	Possible increase owing to bottom-water hypoxia and greater internal cycling	No change

Although several of the above responses are non-unique or potentially ambiguous, collectively they should provide a clear picture of the ecological changes experienced by the study lakes and indicate the most important driver. As it is possible that the lakes have been affected by both N-deposition and warming climate, we will also explore the proportion of ecological change that can be uniquely ascribed to these two drivers using variance partitioning methods (Hall et al. 1999). Variance partitioning uses direct gradient analysis to estimate the fraction of variance in community composition explained by categories of measured variables (environmental, temporal, or spatial factors). In this study we will compare diatom community composition and fossil algal pigments to model hindcasts of lake thermal variables (e.g. length of ice-free season, depth of stratification) and N-deposition trends recorded at nearby NADP sites (e.g. MN18, Fernberg). Evaluation of N-deposition will be limited to the period of deposition monitoring (30 years). This statistical analysis will be performed using the sofware package R.

5. Results and Deliverables

This research is broken into two tasks/results: (1) the collection and dating of sediment cores and, (2) reconstruction of physical and biological changes in the study lakes over the last two centuries. For the first result, the deliverable is a set of dated sediment cores from 12 wilderness lakes fitting the specific morphometric criteria outlined above. This deliverable will also include a GIS analysis of lake surface and watershed areas and the determination of morphometric parameters required for thermal modeling. The second deliverable has two elements: (*a*) the reconstruction of biological change from the sediment cores, and (*b*) the modeled hindcasts of lake thermal structure based on historical meteorological records. The biological reconstructions will include composition of the diatom communities in each lake over time, the relative abundance of other algal groups based on fossil pigments, and trends in primary productivity (carbon and biogenic silica) and nutrients (phosphorus and nitrogen isotopes). This multi-proxy data set should provide a robust picture of past lake conditions which will be compared to modeled changes in lake thermal regime over the last century. Output from the lake thermal modeling will include time trends on the length of the ice-free season, period and depth of stratification, and the presence and duration of bottom water anoxia. These results will provide the information necessary to evaluate the magnitude and timing of ecological change, the role of thermal structure in driving any observed changes, and the relative sensitivity of different lake types to climate forcing.

6. Timetable

The project will require three years to complete. Sediment sampling will occur over the first year of the project. As sediment cores are collected, they will be dated and analyzed. Geochemical analyses will take 18 months, while diatom analysis will require 24 months. Lake hydrodynamic modeling will commence mid-way through the project and will take 12 months. Six months is allotted for synthesis and final reporting. Theses research tasks will be accomplished according to the following schedule. Shaded regions are continuous efforts and X's mark discreet events.

	2011		2012				2013				2014	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Result 1: Lake selection, coring, and dating												
Lake selection and coring												
Sediment core dating												
Watershed and lake mapping												
Product delivery						X						
Result 2: Environmental reconstructions												
Diatom analysis and statistical interpretation												
Sediment chemical analyses												
Hydrodynamic modeling												
Data synthesis												
Product delivery										X		X
Reporting		X		X		X		X		X		X

7. Budget

IV. TOTAL TRUST FUND REQUEST BUDGET 3 years

BUDGET ITEM	AMOUNT
Personnel: **SCWRS Staff:** Amounts are Salary + Benefits. Benefits are 28% of Salary. Dan Engstrom Salary + Benefits 10% /yr 3 yrs 35,500 Mark Edlund Salary + Benefits 10% /yr 3 yrs 25,700 Shawn Schottler Salary + Benefits 25% /yr 3 yrs 64,200 Jim Almendinger Salary + Benefits 10% /yr 3 yrs 26,300	$151,700
Contracts: Analytical Services: Analysis of Pigments, C, & N Isotopes $100/sample	$ 24,000
Equipment/Tools/Supplies: Lab supplies and Sediment coring supplies	$ 4,500
Travel: Travel to Collect sediment cores from Lakes. At least three coring trips.	$ 4,000
Additional Budget Items: **Analytical Services** at St. Croix Watershed Research Station: Includes Lead-210 dating, gamma spectrometry, sample preparation, diatom counting, analysis for total phosphorus, biogenic silica, and sediment composition.	$ 115,800
TOTAL ENVIRONMENT & NATURAL RESOURCES TRUST FUND $ REQUEST	$ 300,000

V. OTHER FUNDS

SOURCE OF FUNDS	AMOUNT	Status
Other Non-State $ Being Applied to Project During Project Period:	NA	
Other State $ Being Applied to Project During Project Period: /	NA	
In-kind Services During Project Period:	NA	
Remaining $ from Current ENRTF Appropriation (if applicable):	NA	
Funding History: This project is an outgrowth of monitoring studies in national park units of the Western Great Lakes region funded by the National Park Service	$ 350,000	ongoing

7. Budget

The requested funds from LCCMR total $300,000. The justification is as follows:

Personnel: Over the three-year study period, Drs. Engstrom, Edlund, and Almendinger will devote 10% (1.2 months per year) and Dr. Schottler 25% (3 months per year) of time to the project (total salaries and fringe benefits of $151,700) The responsibilities of the project manager (Engstrom) include experimental design, project coordination, data synthesis, and report/product preparation. Dr. Edlund will oversee the diatom analyses and Dr. Schottler the core dating and geochemistry. Dr. Almendinger will be responsible for the lake thermal modeling and GIS analysis of the study sites. All four investigators will participate in the field work and assist in writing the interim and final reports.

Contracts: A sum of $24,000 is budgeted to contract with Dr. Peter Leavitt, Department of Biology, at the University of Alberta for analysis of sedimentary pigments and carbon and nitrogen isotopes. The contract will cover 240 samples (20 intervals for each of 12 cores) at $50 for pigments and $50 for C and N. Dr. Leavitt is an internationally recognized expert in the application of these geochemical proxies for environmental reconstruction and will assist in the interpretation of the data. The SCWRS has collaborated on previous research projects with Dr. Leavitt, and the quoted costs represent a preferential rate.

Supplies: A total of $4,500 is budgeted for laboratory and field supplies (core tubes, sample containers, chemicals, analytical reagents/consumables). This amount includes costs for overnight sample shipping to Dr. Leavitt's lab.

Travel expenses: A total of $4,000 is requested for in-state travel to collect core samples and to attend in-state conferences.

Other. Additional funds totaling $115,800 dollars are requested for analytical services at the SCWRS, specifically diatom counting (180 samples @ $450/sample), lead-210 dating (12 cores @ $2,000/core), and total-P and bSi analyses (240 samples @ $45/sample). These costs represent standardized SCWRS rates for both internal and extramural projects.

8. Credentials

The St. Croix Watershed Research Station is nationally recognized for its expertise in the application lake sediment records to understand long-term environmental change, particularly the effects of human activities on water quality, atmospheric chemistry, and biogeochemical processes. Expertise of the four senior researchers who will direct various aspects of this project are as follows: sediment dating and geochemistry (Engstrom), diatom systematics and ecology (Edlund), environmental engineering and chemistry (Schottler), and surface and groundwater hydrology (Almendinger).

DANIEL R. ENGSTROM

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1. *Education*

Ph.D.	1983	University of Minnesota, Minneapolis (Ecology)
M.S.	1975	University of Minnesota, Duluth (Zoology, minor: Botany)
	1971-73	University of Wisconsin, Madison (Zoology: Limnology)
B.A.	1971	University of Minn., Duluth (Zoology, minor: chemistry) Magna cum Laude

2. *Positions*

1999-	Director, St. Croix Watershed Research Station, Science Museum of Minn.
1995-99	Sr. Scientist, St. Croix Watershed Research Station, Science Museum of Minn.
1990-	Adjunct Professor, Dept. of Geology and Geophysics, University of Minnesota
2004-	Adjunct Professor, Water Resources Science, Univ. of Minnesota
1983-95	Research Associate, Limnological Research Center, Univ. of Minnesota

3. *Research Expertise*

My research centers on the use of lake sediment records to understand long-term environmental change, particularly the effects of human activities on water quality, atmospheric chemistry, and biogeochemical processes. Areas of current research include: (1) Atmospheric mercury deposition and cycling; (2) Historic nutrient and contaminant loading to the Mississippi River; and (3) Geochemical fingerprinting suspended sediment in agricultural watersheds.

4. *Recent Publications (of more than 100)*

Yang, H., **D.R. Engstrom**, and N.L. Rose. 2010. Recent changes in atmospheric mercury deposition in the sediments of remote equatorial lakes in the Rwenzori Mountains, Uganda. *Environmental Science and Technology* 44: 6570-6577.

Balogh, S.J., L.D. Triplett, **D.R. Engstrom**, and Y.H. Nollet. 2010. Historical trace metal loading to a large river recorded in the sediments of Lake St. Croix, USA. *J. Paleolimnology* 44: 517-530.

Engstrom, D.R., J.E. Almendinger, and J.A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. *J. Paleolimnology* 41: 563-588.

Triplett, L.D., **D.R. Engstrom**, D.J. Conley, and S.M. Schellhaass. 2008. Silica fluxes and trapping in two contrasting natural impoundments of the upper Mississippi River. *Biogeochem.* 87: 217-230.

Engstrom, D.R., E.B. Swain, and S.J. Balogh. 2007. History of mercury inputs to Minnesota lakes: influences of watershed disturbance and localized atmospheric deposition. *Limnology and Oceanography* 52: 2467-2483.

5. *Professional Affiliations*

American Quaternary Association
American Geophysical Union
American Society of Limnology and Oceanography
Ecological Society of America
North American Lake Management Society
International Society of Limnology

6. *Synergistic Activities*

Executive Committee: *International Paleolimnology Association*, 2006-present

Panel Chair, Sediment-core work group: *Mercury in the Great Lakes Region*, 2008-present

Invited Expert, *National Mercury Monitoring Workshop*, USEPA and other Federal Agencies, Annapolis, MD, May, 2008.

Expert Panel Member: *International Workshop on Environmental Mercury Pollution*, Madison WI 2005-06

Member: Lake Pepin-Mississippi River TMDL Science Advisory Panel, 2006-present

JAMES EDWARD ALMENDINGER

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Education

1988. Ph.D., Ecology. University of Minnesota.
1978. B.A., Botany. Ohio Wesleyan University (Valedictorian; Summa Cum Laude)

Positions

1995- Senior Scientist, St. Croix Watershed Research Station, Science Museum of Minnesota
2000- Adjunct Associate Professor, Univ. of Minn.: Water Resources Science Program; Dept. of Fisheries, Wildlife and Conservation Biology; and Dept. of Geology and Geophysics
1990-95. Hydrologist, U.S. Geological Survey, Mounds View, MN.
1989-90. Fellow, American-Scandinavian Foundation, Univ. of Lund, Sweden.

Research Interests

General:

Watershed hydrology models; land-use and small stream hydrology; Quaternary paleoecology; groundwater/surface-water interactions; wetland hydrology.

Current projects:

(1) Modeling land-use impacts on streams, lower St. Croix basin, MN & WI
(2) Water quality and aquatic biodiversity in western Mongolia
(3) Watershed-scale erosion in agricultural western Minnesota

Professional Memberships

American Ass'n for the Advancement of Science
American Geophysical Union
American Quaternary Association
American Water Resources Association
Geological Society of America
Minnesota Ground Water Association
National Ground Water Association

Selected Papers

Shinneman, A.L.C., **J.E. Almendinger**, C.E. Umbanhowar, M.B. Edlund, and S. Nergui. 2009. Paleolimnologic evidence for recent eutrophication in the Valley of the Great Lakes (Mongolia). Ecosystems 12: 944-960.

Engstrom, D.R., **J.E. Almendinger**, and J.A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. Journal of Paleolimnology 41: 563-588.

Almendinger, J.E., and M.S. Murphy. 2007. Problems and solutions in applying SWAT in the Upper Midwest USA. In Srinivasan, R. (ed.) 4th International SWAT Conference Proceedings. UNESCO-IHE Institute for Water Education, Delft, Netherlands, pp. 398-407.

Clark, J.S., E.C. Grimm, J.J. Donovan, S.C. Fritz, D.R. Engstrom, and **J.E. Almendinger**. 2002. Drought cycles and landscape responses to past aridity on prairies of the northern Great Plains, USA. Ecology 83(3): 595-601.

Engstrom, D.R., S.C. Fritz, **J.E. Almendinger**, and S. Juggins. 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. Nature 408:161-166.

Balogh, S.J., D.R. Engstrom, **J.E. Almendinger**, M.L. Meyer, and D.K. Johnston. 1999. A history of mercury loading in the upper Mississippi River reconstructed from the sediments of Lake Pepin. Environmental Science and Technology 33: 3297-3302.

Almendinger, J.E. 1999. A method to prioritize and monitor wetland restoration for water-quality improvement. Wetlands Ecology and Management 6:241-251.

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Professional Preparation

University of Minnesota, Twin Cities Campus, Biochemistry, B.S. (1987)
University of Michigan, Ann Arbor, Natural Resources, M.S. (1992)
University of Michigan, Ann Arbor, Natural Resources, Ph.D. (1998)
University of Michigan, Science Museum of Minnesota, Post-doc (1998-2001)

Current Appointments

2007-present, Senior Scientist, Science Museum of Minnesota, St. Croix Watershed Research Station
2001-present, Adjunct Faculty, Univerisity of Minnesota, Geology and Geophysics, Water Resources Science

Five Publications Relevant to Proposed Activity

Edlund, M. B., Engstrom, D. R., Triplett, L., Lafrancois, B. M. and Leavitt, P. R. 2009. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology. DOI:10.1007/s10933-008-9296-1

Triplett, L. D., Engstrom, D. R. and **Edlund, M. B.** 2009. A whole-basin stratigraphic record of sediment and phosphorus loading to the St. Croix River, USA. Journal of Paleolimnology DOI:10.1007/s10933-008-9290-7

Shinneman, A. L. C., **Edlund, M. B.**, Almendinger, J. E. and Soninkhishig, N. 2009. Diatoms as indicators of water quality in Western Mongolian lakes: a 54-site calibration set. Journal of Paleolimnology DOI:10.1007/s10933-008-9282-7

Serieyssol, C. A., **Edlund, M. B.** and Kallemeyn, L.W. 2009. Impact of logging, damming, and hydromanagement on two boreal lakes: a paleolimnological before—after, control—impact study. Journal of Paleolimnology DOI:10.1007/s10933-008-9300-9

Edlund, M. B. and Stoermer, E. F. 2000. A 200,000-year, high-resolution record of diatom productivity and community makeup from Lake Baikal shows high correspondence to the marine oxygen-isotope record of climate change. Limnology and Oceanography 45:948-962.

Five Other Significant Publications

Edlund, M. B., Triplett, L. D., Tomasek, M. and Bartilson, K. 2009. From paleo to policy: partitioning of historical point and nonpoint phosphorus loads to the St. Croix River, Minnesota-Wisconsin, USA. Journal of Paleolimnology DOI: 10.1007/s10933-008-9288-1

Reavie, E.D. and **Edlund, M.B.** 2010. Diatoms as indicators of environmental change in rivers, fluvial lakes and impoundments. In Smol, J.P. and Stoermer, E.F. (Eds) The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press. pp 86-97.

Shinneman, A.L.C., Umbanhowar, C.E., Jr., Almendinger, J.E., **Edlund, M.B** and Soninkhishig, N. 2009. Paleolimnologic evidence for recent eutrophication in the Valley of the Great Lakes (Mongolia). Ecosystems 12: 944-960.

Heiskary, S. A., Swain, E. M. and **Edlund, M. B.** 2004. Reconstructing Historical Water Quality in Minnesota Lakes from Fossil Diatoms. Environmental Bulletin No. 4: 1-8.

Edlund, M. B., Taylor, C. M., Schelske, C. L. and Stoermer, E. F. 2000. *Thalassiosira baltica* (Bacillariophyta), a new exotic species in the Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences 57:610-615.

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Education

Ph.D. University of Minnesota, Minneapolis, Minnesota
Environmental Engineering, 1996

B.S. University of Minnesota, Minneapolis, Minnesota
Geotechnical Engineering, 1989

Research

Senior Scientist: St. Croix Watershed Research Station, 1997-
Radioisotopic tracers of sediment sources in agricultural watersheds
New techniques for sampling of suspended sediment, and field erosion
Refine analytical methodology of using radioisotopes as sediment tracers
Quantify the effects of land use-BMP on water quality and hydrology
Coordination and supervision of upland restoration projects

Recent Publications

Schottler, S. P., Engstrom, D. R., and Blumentritt, D. 2010. Fingerprinting sources of sediment in a large agricultural river system, Final Report to Minnesota Pollution Control Agency in fulfillment of Lake Pepin TMDL, CFMS # A94798. *http://www.smm.org/static/science/pdf/scwrs-2010fingerprinting.pdf*

Schottler, S. P., Port J. and DeGolier, T., 2008, Influence of floristic diversity on songbird nesting preferences in a suite of adjacent reconstructed grasslands, Ecological Restoration, v. 26 (3), 195-197.

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Engstrom, D. R., Schottler, S. P., Leavitt, P. R., and Havens K. E. 2006. A Re-evaluation of the cultural eutrophication of Lake Okeechobee using multiproxy sediment records, Ecological Applications, v.16(3), 1194-1206.

Schottler, S.P., Identification of Sediment Sources in an Agricultural Watershed, Final Report to the Legislative Commission on Minnesota's Resources, December 30, 2002

Swackhamer, D.S., Schottler, S.P., and Pearson, R.F_Air-Water Exchange and Mass balance of Toxaphene in the Great Lakes, *Environmental Science and Technology*, v.33, pp. 3864-3872, 1999

9. Dissemination and Use

Findings will be disseminated and archived via reports to LCCMR, peer-reviewed publications, and presentations at conferences. We will also, when appropriate, disseminate results via the media and though exhibits and programming at the Science Museum of Minnesota. The audience is not only the scientific community, but also the public and policymakers. The information derived from this research will provide lake mangers and the public at large with an improved understanding of how climate change may be stressing Minnesota lakes and what future changes may be in store.

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Edlund, M. B. 1994. Additions and confirmations to the algal flora of Itasca State Park. II. Diatoms of Chambers Creek. Journal of the Minnesota Academy of Science **59**.

Edlund, M. B., and J. M. Ramstack. 2006. Diatom-Inferred TP in MCWD Lakes, Final Report 116-04. Minnehaha Creek Watershed District.

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