MINNESOTA
SEA GRANT COLLEGE PROGRAM
RESEARCH COMPLETION REPORT

PI NAME: Euan D. Reavie **PROJECT NUMBER: 00016993**

START DATE: March 2010 **END DATE: September 2012**

PROJECT TITLE: A Whole-Lake Assessment of Long-Term Human Impacts to Lake Superior

OBJECTIVES (please note if these are different than those originally proposed)**:**

- To find the driving factors behind changes occurring in Lake Superior
- To determine the effect of rehabilitation efforts on lake conditions
- To determine whether historical changes in the lake were related to anthropogenic impacts
- To investigate the spatial variation in historical pelagic conditions

METHODS (please note if these are different than those originally proposed)**:**

Sediment cores were collected from depositional areas during the summer of 2010 via the R/V Lake Guardian and the R/V Blue Heron. Cores were sectioned into fine intervals (0.25 cm for diatom samples, 0.5 cm for dating/metals analyses). Sedimentary ^{210}Pb analyses determined ages of sediment layers. Loss on ignition (LOI) analysis of sediments was used to determine water content (at 100° C for 24 hours), organic content (at 550° C for 1 hour), and carbonate content (at 1000° C for 1 hour). Subsamples from the two cores were analyzed for metals and cations by the University of Minnesota, Department of Geology and Geophysics, Aqueous Geochemical Laboratory. Pollen analysis of the stratigraphic *Ambrosia* horizon was used to verify ^{210}Pb results and the timing of European settlement; sample preparation was supported by the University of Minnesota Limnological Research Center. Pollen grains were counted in samples from the Isle Royale core to identify the *Ambrosia* horizon which is well known to increase in sediments following European settlement and deforestation activities in North America. We had originally anticipated analyzing the *Ambrosia* layer from both cores, but after processing difficulties with the eastern core it was deemed time effective to analyze one core. Remaining sample material was freeze-dried and archived to enable future analyses.

Sediment samples were processed for diatoms by personnel at the University of Minnesota Duluth, Natural Resources Research Institute (UMD NRRI), Ely Field Station. A sediment subsample of ~1g was digested with a strong oxidizer and rinsed several times to remove organic residue. Diatoms were settled and dried on coverslips, then mounted for microscopic observation. Samples were analyzed from the pre-European settlement period to develop a baseline of natural variability, and throughout post-European settlement to determine anthropogenic effects. For each sample, at least 400 diatom valves encountered in quantified transects were enumerated to at least species level using oil immersion light microscopy (1000x magnification). Valves were also measured to provide biovolume estimates. Standard floras, Great Lakes species records and the most recent taxonomy iconographs were used to identify diatoms.

The software program R was used for data analyses. Because it is free access and more flexible, R software was used in lieu of software originally listed in the proposal (i.e. CANOCO, C2). Multivariate analysis is being performed to determine the modern relationship of water quality (from our current work on GLNPO plankton surveys) and stressor measures (developed for this study) to diatom assemblages (work is ongoing). We then developed a model using modern diatoms from the Great Lakes, which were

applied to down-core assemblages to reconstruct environmental conditions in Lake Superior over the last ~300 years.

Spatial and temporal dynamics of historic land use patterns were collected from historical records. A database was populated with information from various world wide web and GIS resources, which were tracked to provide metadata and documentation for each value. Transcribed records combined a date, the land use in question (agriculture, mining, human population), the level of the land use (acres, population, mines) and the spatial distribution of the land use (points, lines, and polygons, stationary or moving over time). Historical items were placed on a timeline with annual time-steps from 1700 to 2020. The level associated with each record was rendered into a GIS raster grid specific to each land use type. The level of each land use was summarized within 15 watersheds covering the Lake Superior basin, each watershed of approximately equal area. Post-processing of results allowed reporting of land-use levels for a particular date and/or changes in land-use levels for a particular range of years. Using this database, historical land use data may be generated for all watershed groups combined, or for selected subsets of watershed groups (e.g., only eastern or western basin watersheds, as applied to our corresponding eastern and western sediment core locations). The land use dataset continues to be developed for additional land use variables such as forestry, but at this time the compiled results provide a clear picture of historical activities around Lake Superior. Currently, the database has been employed to describe long-term population dynamics and agricultural and mining activities, and these historical data are being statistically compared with trends in the paleolimnological profiles.

RATIONALE:

The Laurentian Great Lakes are an invaluable resource supporting drinking water and healthy ecosystems as well as multiple industrial and recreational uses. Lake Superior, the least studied of the Great Lakes, is also considered the most pristine. Thus development and anthropogenic impacts, which have been well documented in the other Great Lakes, are not as well understood in Lake Superior. Annual monitoring has revealed significant physical, chemical and biological changes in Lake Superior which need to be understood in a historical context. In addition, stressors continue to threaten the lake, highlighting the importance of documenting natural lake variability in order to understand human influence on historical changes to better understand modern fluctuations.

PARTNERS: (agencies, business/industry, etc)

- Minnesota Sea Grant
- The Great Lakes Aquarium (outreach)
- University of Minnesota Duluth Viz Lab (outreach)
- Science Museum of Minnesota and St. Croix Watershed Research Station (isotope analyses)
- LacCore and the University of Minnesota Limnological Research Center (pollen processing)
- University of Minnesota Aqueous Geochemical Laboratory (metals processing)
- Large Lakes Observatory (ship and equipment use for field work)
- USEPA Great Lakes National Program Office (ship and equipment use for field work, provision of model data)

BENEFITS to research, industry, or the environment: (Be specific about dollar amounts (if they apply) when discussing benefits to existing or future industries)

A better understanding of historical lake changes and links to anthropogenic impacts are beneficial for ongoing and future research of the lake. The lake can be better preserved, protected and restored by

understanding the links to human impacts in the watershed. Further, legislation and industry can focus objectives and resources by determining which practices most influence water quality.

Specifically, this study revealed that, despite its size, Lake Superior is highly sensitive to anthropogenic inputs such as nutrients. Also, the lake responded to remedial measures reducing nutrients in the form of improved pelagic water quality. These are important lessons for lake management and show the significance of ongoing remedial activities such as sewage treatment.

This work especially informs future research by providing a flexible historical database of human activities around the lake and greater clarity on water quality aspects that require further work, such as clear reasons for changes in lake biology and water quality in recent decades. This study of historical lake conditions allows a better understanding of the driving factors influencing Lake Superior. Further, studies such as this help put into context enigmatic changes noted during modern monitoring surveys. Recent observed changes may not be due to natural variability, but rather reflect stressors like human activity, invasive species and climate change.

RESULTS SUMMARY: (500 words maximum; if this is continuing research, summarize your most recent findings).

We investigated the long-term ecological history of Lake Superior by detailed paleolimnological analysis of two sediment cores to determine the effects of anthropogenic activities on historical water quality. Lake Superior, although widely considered the most pristine of the Great Lakes, did show clear evidence of water quality changes related to anthropogenic stressors. Cluster analysis defined distinct water quality eras based on diatom taxa. Fluctuations in dominant taxa pointed to changes in the water quality particularly in the early 20th century. Eutrophication coincided with human patterns in land use, with a decrease in water quality corresponding to European settlement and consequent stressors such as logging, agriculture, and mining. Nutrient reconstructions suggest that the phosphorus load in Lake Superior nearly doubled due to excess nutrient flux to the aquatic system. Since reductions in agricultural activities, removal of phosphates in detergents, construction of sewage treatment facilities, and other activities as mandated under the Great Lakes Water Quality Agreement (under the Clean Water Act), water quality largely recovered. Other indicators (organic and inorganic composition, trace metals, and others) further provide evidence of environmental stressors such as mining inputs throughout the 20th century, followed by partial recovery. Despite recent improvements, current Lake Superior water quality and biological character has not reverted to pre-settlement condition; current environmental condition appears to be driven by variables other than nutrients. Relationships to additional drivers (e.g. climate) are currently under investigation.

We detected spatial patterns of disturbance within the lake. There were lake-wide trends of similar disturbance features, but the central core, near Isle Royale, showed more localized trends related to mining and urban development around the north shore and the twin ports of Duluth and Superior. The eastern core, near the lake outlet, revealed a more integrated assimilation of lake-wide nutrient flux and revealed a lag in the time required for changes in water quality to occur in the eastern portion of the lake.

We have created a historical database for landscape changes in the watershed, which can be related to water quality changes at various spatial scales. A diatom-based transfer function for nutrients, created using modern data from the long-term GLNPO monitoring program, has been created to reconstruct historical water quality conditions. These new tools were applied in this study and are available for future applications.

PROJECT WEBSITE URL:

TARGET AUDIENCES: (Audiences interested in your results: scientific, agency, commercial, and general public)

This study would be of interest to other Great Lakes researchers with various research foci as well as government agencies and industrial users in determining management plans. The concentrated outreach efforts should further reach a broad general public audience via the Great Lakes Aquarium and the Sea Grant website as well as popular websites like YouTube.

ACCOMPLISHMENTS

1. Success in meeting objectives: (describe obstacles and how overcome, if they were, or why insurmountable)

Lake Superior is notoriously difficult to characterize because of its large size and physical complexity. One of the major sampling difficulties facing this project was known uneven sedimentation and diatom preservation in Lake Superior. Our eastern core location near Whitefish Point was previously sampled in the 1970's and was subject to a detailed historical diatom sedimentary analysis. Knowing this allowed us to choose a location with previously documented historical changes and known intact paleolimnological profile. Thanks to a collaboration with Dr. Sergei Katsev (LLO), who had some data on sediment accumulation in western Lake Superior, we were able to locate an additional core location (collected near Isle Royale) for detailed diatom analysis.

The two cores were analyzed in detail for diatoms, isotopes, organic and inorganic material, metals and other compounds. The Isle Royale core was analyzed for *Ambrosia* pollen to correspond with isotope dating. Terry Brown and Meijun Cai summarized historical landscape changes in the watershed and created a database to access dataset spatial scale parameters.

Analyses determined natural variability in the lake, relationships to watershed stressors and spatial variability between the two core regions. We were thus able to meet our objectives by finding linkages to variables driving historical changes in Lake Superior, including anthropogenic impacts. We also noted positive human influences by observing that rehabilitation efforts had a marked influence on improved water quality.

We developed two new tools that will be used in future investigations: (1) a diatom transfer function using modern data from the GLNPO long-term monitoring program; (2) a historical database of stressor activities around the lake.

Significant outreach has taken place due to Victoria Chraïbi's efforts with the Great Lakes Aquarium, teaching a paleolimnology course to educators and working closely with aquarium staff. Ms. Chraïbi created an educational paleolimnology game that will likely be modeled for the upcoming display at the aquarium. The display will focus on human impact, diatoms, microscopy, and paleolimnological techniques. Mock-ups of the display have been developed with an anticipated opening late fall/early winter 2012. Additional outreach includes the development of an educational video through collaboration with Dustin Thompson of UMD's Viz lab. The educational video series will be accessible via Sea Grant's website this fall. All of this outreach work has been performed in the context of the concurrent Lake Superior paleolimnology study.

Given the substantial output from this study we believe that we surpassed all of the initial objectives and have had significant success. Continued development of results and eventual publication in international literature will ensure these valuable data continue to be shared.

2. List of most exciting results/findings: (bullet format)

- Intact paleoecological profiles occur in Lake Superior and historical changes in water quality can be inferred using fossil assemblages.
- Historical changes related to human impacts have been found in the lake: both deterioration of water quality conditions with landscape modification, resulting in nutrient enrichment, and improvement with focused legislation such as the Clean Water Act and its subsidiary the Great Lakes Water Quality Agreement.
- Despite recent improvements, current Lake Superior water quality and biological character has not reverted to pre-settlement condition; current environmental condition appears to be driven by variables other than nutrients. Relationships to additional drivers (e.g. climate) are currently under investigation.
- Inferred long-term conditions are different based on cores collected from different places in the lake; regional differences noted between the two locations reflect differences in timing of impacts as well as more regionally focused impacts such as mining influences at the western location.

3. New research directions resulting from this research:

This work provided a pilot assessment for continued paleolimnology work on the Great Lakes, funded through the USEPA's Great Lakes National Program Office. We are currently collecting and analyzing sediment cores from the remaining Great Lakes to gain a better understanding of human impacts in the basin as a whole.

4. Awards or commendations to PIs or students:

Fulbright Canada-RBC Eco-Leadership Program Grant 2011. Grant partners were Victoria Chraïbi, DNR Minnaqua Program, and Great Lakes Aquarium: for Science Institute for Educators workshops, lesson plan and teaching kit development, and creation of a teaching library at the aquarium.

Fulbright Canada-RBC Eco-Leadership Program Grant 2012. Grant partners were Victoria Chraïbi, Lake Superior Zoo, UMD-NRRI, Duluth City Parks, and Glensheen Historic Estate: education about bats for schools in Duluth and the Iron Range as well as installation of bat houses and a family scavenger hunt in various Duluth City Parks.

5. Publications in refereed journals resulting from this research:

We expect to have two major publications from the research. The first one, derived largely from Ms. Chraïbi's Water Resources Sciences thesis, will detail historical human impacts on the lakes using the two cores, while addressing spatial considerations and comparing with a previous paleolimnological study from a core in the same eastern basin location. A tentative submission for this article is as follows: Chraïbi, V., A.R. Kireta, E.D. Reavie, T.N. Brown, M. Cai 2013. Anthropocene paleolimnology of Lake Superior (in preparation).

The second publication will be a more in-depth study examining statistical relationships among the many indicators used in this study (diatoms, pollen, metals, organic and inorganic material, land-based stressors, etc.). This second study is intended to clarify surrogacyamong paleolimnological indicators.

6a. Graduate students supported on this project: (please include full name of student)

Victoria Shaw Chraïbi

6b. Graduate student degrees granted and thesis titles: (authors, titles, dates, school and department granting degree, name of advisor if different from lead PI; please ensure that Sea Grant receives a bound copy of each thesis)
Victoria Shaw Chraïbi, M.S., A whole-lake assessment of long-term human impacts to Lake Superior. To be completed Fall 2012, University of Minnesota Duluth, Water Resources Sciences, Advised by Dr. Euan Reavie.

6c. Location and title of job or position attained by graduate student(s) following graduation: (include contact information, if known)

PhD candidate at the University of Nebraska-Lincoln under Dr. Sherilyn Fritz studying paleoecology in regards to community resilience and adaptive management in Yellowstone National Park, also participating in the NSF IGERT program.
214 Bessey Hall, Lincoln, NE 68588-0340, phone 402-472-6431, supervisor Sfritz2@unl.edu
New email vchraibi@huskers.unl.edu

6d. Number of undergraduates that worked on this project: (include number that continued on to graduate school in science or to a career in science, if known).

None.

7. Presentations at professional meetings/conferences: (please list presenter, date, title, location, type -- poster or platform)

Amy Kireta - 6/2/11 oral presentation
Lake Superior ecological history and current trajectory as told by diatoms.
Amy Kireta, Euan Reavie, Lisa Allinger, Victoria Chraïbi
International Association of Great Lakes Research 2011: Duluth, MN

Victoria Chraïbi - 9/7/11 oral presentation
A diatom-based paleolimnological study of Lake Superior.
Victoria Chraïbi, Amy Kireta, Euan Reavie, Lisa Allinger.
21st North American Diatom Symposium September 14-18: Flathead Lake Biological Station, Montana

8. Outreach publications and presentations: (include author/presenter, date, title, location, audience type)

Victoria Shaw Chraïbi - 3/1/11 Science institute for Educators, teacher workshop
Using diatoms to understand the ancient lake (Paleolimnology)
Great Lakes Aquarium: Victoria created a paleo game teaching tool that was distributed at the workshop (Paleolimnology with Diatoms Model)

Project interview which aired 6/29/11 on KUMD 103.3 FM
Amy Kireta and Euan Reavie

9. Other outreach activities:

- Ms. Chraïbi created a paleo game teaching tool that was distributed at the workshop (Paleolimnology with Diatoms Model).
- A series of videos are being created to be used on the Sea Grant site describing the research and findings.

- A permanent display about paleolimnology and human impacts in Lake Superior is being created for the Great Lakes Aquarium set to open sometime in Fall/Winter 2012.

10. Describe ongoing interactions with Sea Grant Outreach staff:

Sharon Moen, Jesse Schomberg, and Cindy Hagley were involved from beginning with development of the video series and provided useful guidance and information. We plan to continue using Sea Grant staff expertise to increase outreach efforts in future projects.

11. Describe interactions with government agencies, other universities, or industries related to your research, including future plans to extend your results to government, industry, or the public:

The public will have access to this research and the findings via the educational video on Sea Grant's website and via the display at the Great Lakes Aquarium. The take home message for the aquarium display is that human impact (both positive and negative) can be seen in an apparently pristine system such as Lake Superior. Also, we hope to provide an appreciation for diatoms and the microscopic world and what we learn from it, as well as educate on paleolimnology, its usefulness and how all of us are scientists, while showcasing women who worked on this project.

The video will be instructional and useful to educators in describing this technique and providing a hands-on application of ecological data.

Other researchers, government entities, and industries can use the findings of this research to better understand the extent of human influence on historical changes in the lake. These results can help promote useful protective legislation, as it shows effective response to previous regulation (e.g. the Clean Water Act).

12. Is anyone applying your research results at this time? Explain.

The researchers of the current study are building off of this research to investigate paleolimnological changes in the other Great Lakes. After publication in international literature we anticipate that others will gain from this study.

13. List of products, patents, websites, programs, software, etc, resulting from this project:

- A display at the Great Lakes Aquarium.
- An instructional video via the Sea Grant website.
- A diatom-based transfer function that may be applied to assess modern or historical stressors elsewhere in the region.
- A detailed database of watershed stressors.

14. If you have graphics, pictures, or video which showcase your project or results that we could use on websites or in our publications, please briefly describe them.

- We are specifically creating a video with an expert at UMD's Viz lab for the Sea Grant website. We are intending this to be used by any visitor to the website and could be a resource for educators of seventh grade and up with use of supplementary data.
- Several field work and diatom specimen digital photos and videos.

PERFORMANCE MEASURES (see attached guidance for definitions and examples. We are required to provide performance measures to National Sea Grant each year). You may not have anything at all in some of these categories, and that is expected. All we need at this point is a number and a sentence or two explanations.

Measure 1: Economic and societal benefits derived from the discovery and application of new sustainable coastal, ocean, and Great Lakes products from the sea.

None- The nature of this study does not derive physical products from Lake Superior.

Measure 2: Cumulative number of coastal, marine, and Great Lakes issue-based forecast capabilities developed and used for management.

Two: The diatom inference model can be used to back-cast nutrient levels and historical water quality changes, and can thus be used for management forecasts. Second, the paleolimnological investigation overall provides a trajectory for lake condition which may be used to inform management and/or prepare for future conditions that may result from continued environmental change.

Measure 3: Percentage/number of tools, technologies, and information services that are used by managers (NOAA and/or its partners and customers) to improve ecosystem-based management.

Two Major Products: A diatom inference model and a detailed watershed stressor database.