

2010 Project Abstract

For the Period Ending June 30, 2013

PROJECT TITLE: Quantifying Carbon Burial in Healthy Minnesota Wetlands

PROJECT MANAGER: James Cotner

AFFILIATION: University of Minnesota-Twin Cities

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FUNDING SOURCE: Environment and Natural Resources Trust Fund

LEGAL CITATION: M.L. 2010, Chp. 362, Sec. 2, Subd. 3g

APPROPRIATION AMOUNT: \$144,000

Overall Project Outcome and Results:

We examined the potential for shallow lakes to mitigate carbon dioxide release from fossil fuels. The CO₂ concentration in the atmosphere is increasing and it is a greenhouse gas that has been strongly connected to climate change on Earth. The state of Minnesota emits over 150 million metric tons of CO₂ annually due to fossil fuel burning and a stated goal is to stabilize releases at 1990 levels. Reaching this goal will require both minimizing sources and maximizing sinks such as lakes.

To determine how much CO₂ is removed from the atmosphere by shallow lakes, we collected sediment samples from over 100 lakes throughout the state, determined how much organic carbon resides in the sediments and determined the burial rate using a new method that is based on ²¹⁰Pb dating. Our goals were to identify important variables that facilitate carbon burial and to estimate burial rates for the entire state. We found that shallow lakes bury organic carbon at very high rates compared to other landscape features and that effective burial is facilitated by high rates of productivity that occurs in these systems; anaerobic (no oxygen) conditions, when they occur, particularly in the wintertime under the ice, also facilitate increased carbon burial. Although burial represents a large quantity of carbon, about 6 Tg per year (or 6 million metric tons), the State of Minnesota releases about 150 million metric tons of carbon per year through the burning of fossil fuels.

In addition to the scientific results of our work, this project has helped train 10 undergraduate students from both the University of St. Thomas and University of Minnesota, two graduate students at the University of Minnesota and one post-doctoral fellow for two years.

More information on the results of this project can be found in our final project report.

Project Results Use and Dissemination

The results from this project have been incorporated into materials for use in the classroom at St. Thomas and University of Minnesota. Cotner and Zimmer have used material from this project in lectures they have given locally, nationally and internationally (Sweden, Brazil, Japan). At the recent Ecological Society of America

annual meeting, members of our team presented 11 posters and/or oral presentations that were very well received. We also organized a special session on terrestrial-aquatic linkages that had a strong focus on carbon burial. This was an extremely well-attended session at this international meeting. Also, 6 members of our group (Cotner, Zimmer, Hobbs and Ramstack-Hobbs, Herwig, and Hanson) presented results from this project at a Shallow Lakes Workshop that we helped organize in Fergus Falls this past August. This workshop was completely full and was attended by resource managers from throughout the state. Cotner has also been presenting some of this work through informal education talks that he has been giving in the past 18 months to various groups (mostly senior citizens) in the Twin Cities area. He has given approximately 20 presentations that have focused on marine and freshwater resources. Lastly, we have published three papers in the scientific literature based on results from this and a related project funded through the National Science Foundation. We have four other papers that are either currently being reviewed or that will be submitted by June 2014.

Environment and Natural Resources Trust Fund (ENRTF) 2010 Work Program-Final Report

Date of Report: 9 Dec 2013

Final report

Date of Work Program Approval:

Project Completion Date: 30 June 2013

I. PROJECT TITLE: 220G – 2010 - Quantifying Carbon Burial in Healthy Minnesota Wetlands

Project Manager: James Cotner

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Location: This project is focused on the entire state, but we will sample lakes in the six shaded study areas shown in Figure 1, representing five of Minnesota's ecoregions. This will allow us to integrate our results over the entire state.

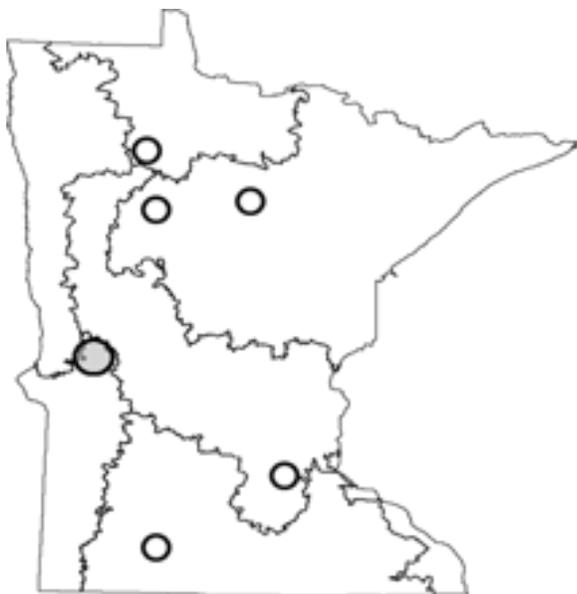


Figure 1. The location of the proposed project. The shaded grey circle shows the location of our NSF work on 13 lakes in western MN. Hollow circles show the location of additional lakes to be studied with LCCMR funds, as well as additional lakes in the western Minnesota study area. Lines represent boundaries of Minnesota's seven ecoregions. The scope of the project includes the entire state but efforts will be focused on lakes in various ecoregions.

Total ENRTF Project Budget:	ENRTF Appropriation	\$144,000
	Minus Amount Spent:	\$143,917
	Equal Balance:	\$83

Legal Citation: M.L. 2010, Chp. 362, Sec. 2, Subd. 3g

Appropriation Language:

\$144,000 is from the trust fund to the Board of Regents of the University of Minnesota to determine the potential for carbon sequestration in Minnesota's shallow lakes and wetlands. This appropriation is available until June 30, 2013, by which time the project must be completed and final products delivered.

II. FINAL PROJECT SUMMARY AND RESULTS:

We examined the potential for shallow lakes to mitigate carbon dioxide release from fossil fuels. The CO₂ concentration in the atmosphere is increasing and it is a greenhouse gas that has been strongly connected to climate change on Earth. The state of Minnesota emits over 150 million metric tons of CO₂ annually due to fossil fuel burning and a stated goal is to stabilize releases at 1990 levels. Reaching this goal will require both minimizing sources and maximizing sinks such as lakes.

To determine how much CO₂ is removed from the atmosphere by shallow lakes, we collected sediment samples from over 100 lakes throughout the state, determined how much organic carbon resides in the sediments and determined the burial rate using a new method that is based on ²¹⁰Pb dating. Our goals were to identify important variables that facilitate carbon burial and to estimate burial rates for the entire state. We found that shallow lakes bury organic carbon at very high rates compared to other landscape features and that effective burial is facilitated by high rates of productivity that occurs in these systems; anaerobic (no oxygen) conditions, when they occur, particularly in the wintertime under the ice, also facilitate increased carbon burial. Although burial represents a large quantity of carbon, about 6 Tg per year (or 6 million metric tons), the State of Minnesota releases about 150 million metric tons of carbon per year through the burning of fossil fuels.

In addition to the scientific results of our work, this project has helped train 10 undergraduate students from both the University of St. Thomas and University of Minnesota, two graduate students at the University of Minnesota and one post-doctoral fellow for two years.

Project Results Use and Dissemination

The results from this project have been incorporated into materials for use in the class room at St. Thomas and University of Minnesota. Cotner and Zimmer have used material from this project in lectures they have given locally, nationally and internationally (Sweden, Brazil, Japan). At the recent Ecological Society of America annual meeting, members of our team presented 11 posters and/or oral presentations that were very well received. We also organized a special session on terrestrial-aquatic linkages that had a strong focus on carbon burial. This was an extremely well-attended

session at this international meeting. Also, 6 members of our group (Cotner, Zimmer, Hobbs and Ramstack-Hobbs, Herwig, and Hanson) presented results from this project at a Shallow Lakes Workshop that we helped organize in Fergus Falls this past August. This workshop was completely full and was attended by resource managers from throughout the state. Cotner has also been presenting some of this work through informal education talks that he has been giving in the past 18 months to various groups (mostly senior citizens) in the Twin Cities area. He has given approximately 20 presentations that have focused on marine and freshwater resources. Lastly, we have published three papers in the scientific literature based on results from this and a related project funded through the National Science Foundation. We have four other papers that are either currently being reviewed or that will be submitted by June 2014.

III. PROGRESS SUMMARY AS OF:

15 Aug 2013

In the last few months of this project, we have continued to make progress in terms of understanding the burial of organic carbon in Prairie Pothole lakes and wetlands as well as shallow lakes throughout the entire state of Minnesota. As mentioned in our last report, we planned a special session at the annual Ecological Society of America Meeting that was held here in Minneapolis in August. There were over 15 talks and posters presented related to our topic of 'Terrestrial-aquatic linkages of nutrients and carbon'. In general, there was a great deal of excitement for the session and it was extremely well-attended. Another important accomplishment in the last period of our funding was that the L&O Methods paper that we submitted was accepted and is now published: <http://aslo.org/lomethods/free/2013/0316.pdf>. Three other papers are either currently being reviewed or are in various stages of preparation for submission to journals.

One of the key overall outcomes of our research is that carbon dynamics are incredibly similar among shallow lakes in clear (macrophyte-dominated) and turbid (phytoplankton-dominated) states. We did not expect this when we began our research. This argues that despite vast differences in community composition, ecosystem-scale processes are very similar. Relatedly, another important result that came out of this work is that shallow lakes bury a great deal of organic carbon into their sediments. We found that lakes throughout the state bury, on average, more than 100 grams of organic carbon per square meter per year and that the burial actually differs very little in different regions of the state and among lakes in different states (turbid or clear). These values are quite high but in the range of values that others have observed in other parts of the world. What it means is that these shallow lakes are extremely effective in removing CO₂ from the atmosphere and putting that CO₂ into the sediments where it can remain for a very long period of time, perhaps hundreds to thousands of years. Therefore, an important management outcome is that it is certainly reasonable to take advantage of these systems for removing CO₂ from the atmosphere. If we assume that about 23% of the total land area of Minnesota is covered by freshwaters with similar burial properties, that means that about 6 Tg (10¹² grams or 6 million metric tons) of CO₂ are buried in our shallow lakes annually. This is a very large amount of carbon, but to help put it in context, this is about 4% of the total amount of CO₂ released in the state

by burning fossil fuels. It is nonetheless an important value for managers to be aware of as we likely could increase burial by a factor of 2 or more.

31 December 2012

During this past quarter, we have made considerable progress on our LCCMR project. As we had proposed, a great deal of progress has been made towards estimating the rate at which organic carbon is accumulating in the sediments of each of our study lakes (80 in total). We have refined a method allowing us to acquire an estimate for each individual lake. This method is novel and represents a significant contribution to the scientific community. A manuscript of this method has been submitted to the peer-reviewed journal *Limnology and Oceanography Methods* (Hobbs et al.). While the manuscript was being prepared, sediment samples were being analyzed for ^{210}Pb to implement this new method into our study. This analysis is near completion and we can move to final stage of the project, which is comparing these carbon burial rates to landscape and in-lake data to ascertain possible drivers of burial to Minnesota wetlands. Furthermore, this analysis will allow us to determine whether these systems act as relevant C-sinks in the context of carbon trading legislation and markets.

Hobbs (project post-doc), Cotner and Zimmer have also organized a session at the upcoming Ecological Society of America Annual Meeting to be held in Minneapolis August 2013. This session will focus on measuring the movement of nutrients and carbon from terrestrial to aquatic ecosystems through time and space. Work from this project will feature prominently in this session of invited talks by internationally recognized scientists.

Published papers:

Hobbs, WO, DR Engstrom, SP Scottler, KD Zimmer, and JB Cotner. "Estimating Modern Carbon Burial Rates in Lakes Using a Single Sediment Sample." *LIMNOLOGY AND OCEANOGRAPHY-METHODS* 11 (2013): doi:10.4319/lom.2013.11.316.

Theissen, Kevin M, William O Hobbs, Joy M Ramstack Hobbs, Kyle D Zimmer, Leah M Domine, James B Cotner, and Shinya Sugita. "The Altered Ecology of Lake Christina: A Record of Regime Shifts, Land-use Change, and Management From a Temperate Shallow Lake." *Sci Total Environ* 433 (2012): doi:10.1016/j.scitotenv.2012.06.068.

30 June 2012

During this quarter, we prepared and analyzed hundreds of samples collected through the study for analyses of organic carbon and nitrogen. We are currently using these data and data from additional lakes made available to us from Dr. Dan Engstrom (St. Croix Watershed Research Station) to calibrate the data from our lakes. We are in the process of developing two manuscripts that should be submitted in the next 6-8 months describing a new technique for estimating carbon burial in lakes. This is an important development because it will allow more estimates of carbon burial from many lakes in Minnesota and elsewhere. The second manuscript will make estimates of carbon burial from the across the entire state using the lakes we sampled in this study.

31 December 2011

Prior to field work this summer, a new microprofiling system for the measurement of oxygen, pH, and sulfides in the lake surface sediments was acquired with additional in-kind funds for use during the 2011 field campaign. This sensitive instrument allows us to directly measure the penetration of oxygen into the sediments at the sub-millimeter scale in a short (~10cm) sediment core, which is important for calculating the efficiency of C-burial in the lake sediments. Over 70 lakes were sampled this past summer and fall; all field work has now been completed for this project. Combined with the lakes sampled in 2010 there are a total of 85 shallow lakes across the 5 ecoregions represented in our dataset. The microprofiling system was set-up in semi-permanent lab spaces while in the field and used to collect data on 78 lakes (with triplicate profiles measured for each sediment core). Eight undergraduates were trained in field and lab methods during the field season.

30 June 2011

During this quarter, we hired the post-doctoral fellow (Dr. Will Hobbs) that will be conducting the research on shallow lakes this summer and into the fall. This spring he procured a new instrument that will be used for characterizing the sediments in five different ecoregions of the state. Initial cores were collected to begin to characterize the penetration of dissolved oxygen into the sediments, a key parameter that is related to burial of organic carbon in these sediments. The cores are also being analyzed for carbon content by undergraduate students at the University of St Thomas. Later yet this summer, lakes in all five of the ecoregions will be sampled by collecting cores and removing sub-samples for determination of the quantity of organic carbon and dissolved oxygen present. In some of our NSF-supported research in the western Minnesota ecoregion, we have found that dissolved oxygen levels are an important parameter to degradation of organic matter that occurs in the water column but we do not know yet if this is an important parameter that has an important impact on degradation of material once it is buried in the sediments. We will use ^{210}Pb to characterize the burial rates of carbon in these cores.

31 December 2010

We spent this period establishing collaborations with the Minnesota DNR, recruiting and hiring personnel, and collecting initial sediment cores for estimating carbon burial. We successfully recruited a postdoctoral associate (Dr. Will Hobbs) for this project this past fall, and he will begin working on the grant this spring. We also recruited a University of St. Thomas undergraduate who will begin working on sediment cores in January. A collaborative agreement has also been established between the University of Minnesota and the University of St Thomas to manage the funds. We also established our collaboration with Mark Hanson and Brian Herwig of the Minnesota DNR to share data being collected with their LCCMR grant (Cotner and Zimmer are collaborators on the Hanson LCCMR grant). We will collect and use surface sediment cores to estimate carbon burial rates in the 127 lakes being sampled in the Hanson LCCMR project, and the DNR data will allow us to identify variables influencing carbon burial rates in Minnesota shallow lakes (watershed land use, lake depth, abundance of fish, etc.). We began collecting sediment cores this past fall from 18 lakes, and these samples will be processed this winter. With Dr. Hobbs on board, coring will continue next spring. In summary, the first six months on this project were spent hiring, working out sampling

and analytical logistics, and establishing collaborations. At this point, we have not spent any of our allocated funds, but we will begin to spend our funds in January of 2011.

Amendment Request (05/19/11):

This summer we will collect sediment samples from lakes in all five ecoregions. One of the key variables that affects organic matter degradation in sediments that we have examined as part of our NSF study is the amount of time that organic carbon is exposed to oxygen in the water before it is ultimately buried into anoxic sediments. In order to determine the time of oxygen exposure, one needs to know the age of the sediments at various depths (which we are already determining) and how deep into the sediments dissolved oxygen penetrates. It is this latter variable that we will be able to measure precisely with the instrumentation that we plan to purchase. Previously, we had planned to assume that the penetration depth would be relatively uniform across the five ecoregions but given that there are profound differences in the amount of organic matter as well as the density of the sediments, we expect that there could be large differences in this parameter. With permission from the LCCMR, we would move \$5546 from our 'Supplies' portion of our budget into the 'Capital equipment over \$3500' category. It should be noted that this expenditure will cover about one-third of the cost of the equipment we will purchase. The remainder of funds will come from our NSF funds and from another professor's funds at the University of Minnesota who intends to use this equipment when we are not using it. The instrumentation we will purchase is a microelectrode system that includes several dissolved oxygen sensors, a micromanipulator for moving the sensor through the sediments and software for interpreting the measurements.

Amendment Approved: 05/19/2011

IV. OUTLINE OF FINAL PROJECT RESULTS:

RESULT 1: Estimate the statewide potential for shallow lakes to bury carbon in their sediments, and calculate the statewide potential for shallow lakes to serve as carbon credits.

Description: We estimated both temporal and spatial variability in carbon storage in shallow lakes, scaling estimates of carbon storage in individual lakes to estimates for Minnesota's ecoregions, and estimated the potential for Minnesota's shallow lakes to remove carbon and develop estimates of carbon credits in the carbon trading market.

Summary Budget Information for Result 1:

ENRTF Budget:	\$144,000
Amount Spent:	\$143,917
Balance:	\$83

Deliverable	Completion Date	Budget

1. Identify variables driving carbon storage in each ecoregion and provide an estimate of carbon buried for individual lakes in each ecoregion, total burial for each ecoregion, as well as statewide burial of carbon in shallow lakes	30 Jun 2012	\$84,550
2. Convert estimates of carbon burial by shallow lakes into estimates of potential carbon credits for each ecoregion and the entire state.	30 Jun 2013	\$59,450

Result Completion Date: 30 June 2013

Result Status as of 31 December 2010:

We successfully recruited a postdoctoral associate (Dr. Will Hobbs) for this project this past fall, and he will begin working on the grant this spring. Dr. Hobbs has an extensive history of collecting sediment cores from lakes, and also has experience working in shallow lakes in Minnesota. We also recruited a University of St Thomas undergraduate research assistant who also has experience working on lake sediment

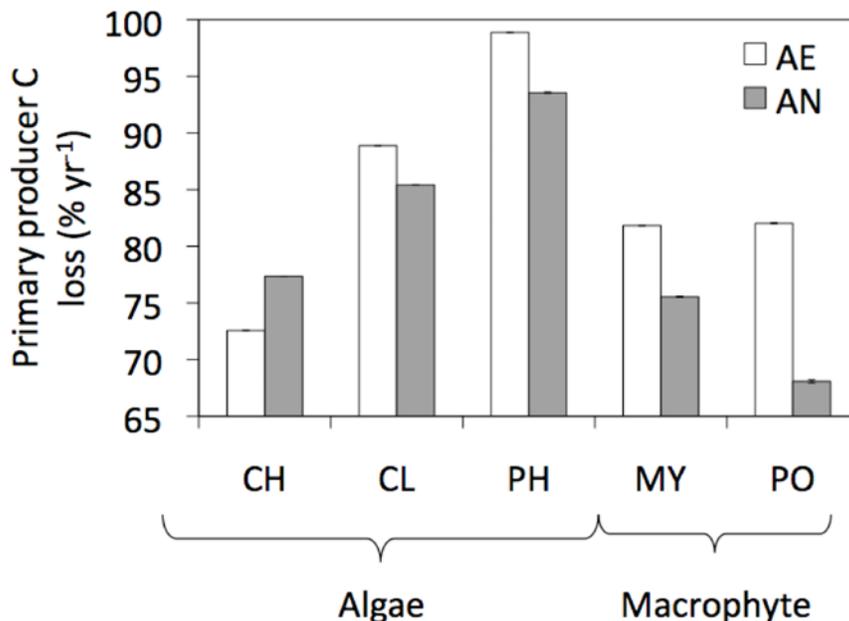


Figure 2. The percentage of organic carbon loss in different types of plants found in shallow lakes in the western ecoregion of Minnesota (CH-Chara; CL- Cladophora; PH- phytoplankton; MY-Myriophyllum; PO- Potamogeton). Note that, with the exception of Chara, all of the plants decomposed at faster rates, i.e., higher loss rates, under aerobic-oxygenated conditions.

cores, and he will begin working on the project in January.

We also established our collaboration with Mark Hanson and Brian Herwig of the Minnesota DNR to share data being collected with their LCCMR grant. The PIs on this LCCMR grant (Cotner and Zimmer) are also collaborators on the Hanson LCCMR grant, which made the collaboration and coordination between the two projects much easier to establish. Hanson has provided us with the location of the 127 shallow lakes they are studying in five different regions of the state. We have already collected cores from 18 of the lakes and will collect surface sediment cores from additional lakes over the next two years and analyze them for concentrations of inorganic carbon, organic carbon, nitrogen, and phosphorus. We will also measure dissolved oxygen levels in the cores to calculate carbon burial efficiency. The cores will be ^{210}Pb dated, allowing us to estimate carbon burial rates and efficiency in all 127 shallow lakes. Using data collected by Hanson on abundance of fish, algae, aquatic plants, nutrient levels, and watershed features, we will then determine the primary drivers of recent carbon burial in Minnesota shallow lakes.

We collected initial sediment cores from 12 lakes in the Alexandria study area and 6 lakes in the Twin Cities Metropolitan area this past fall. Now that Dr. Hobbs is on board, these cores will be analyzed this winter and more cores will be collected this spring. Collection of cores from the other 115 lakes will begin in earnest this spring, and we expect to core half the lakes this summer and the other half in summer of 2012.

Our first six months on this project were spent on hiring, logistics, and establishing collaborations. Thus, we have spent only \$2,500 of the allocated funds from LCCMR, but the activity on this project will increase significantly in January of 2011.

Result Status as of 30 June 2011:

To identify variables that contribute to organic carbon burial in survey lakes, we will be collecting cores from all 5 ecoregions this summer to (a) measure the quantity of organic carbon buried in short cores and also to determine how far dissolved oxygen penetrates into the sediments in each of the regions. Similar work that is being performed by us as part of our related NSF study has demonstrated that the amount of dissolved oxygen exposure of organic matter can play an important role in determining how quickly the organic matter degrades (Fig. 2). These data demonstrated that different plants typically degraded faster when oxygen was present with one exception (*Chara* sp.). Relatedly, as part of our joint project with DNR-Fisheries, we have quantified the plant and chlorophyll biomass in all of the lakes that we will be sampling this year and have found that the plant biomass varies quite substantially from 0 to 7.7 kg per m². This large amount of variation is important, because we expect that macrophyte plant biomass should be an important variable in organic carbon burial.

We have also quantified organic carbon burial rates in some of these western Minnesota shallow lakes and presently our results indicate that organic carbon burial rates have increased by a factor of 2-5 since European settlement in this region of

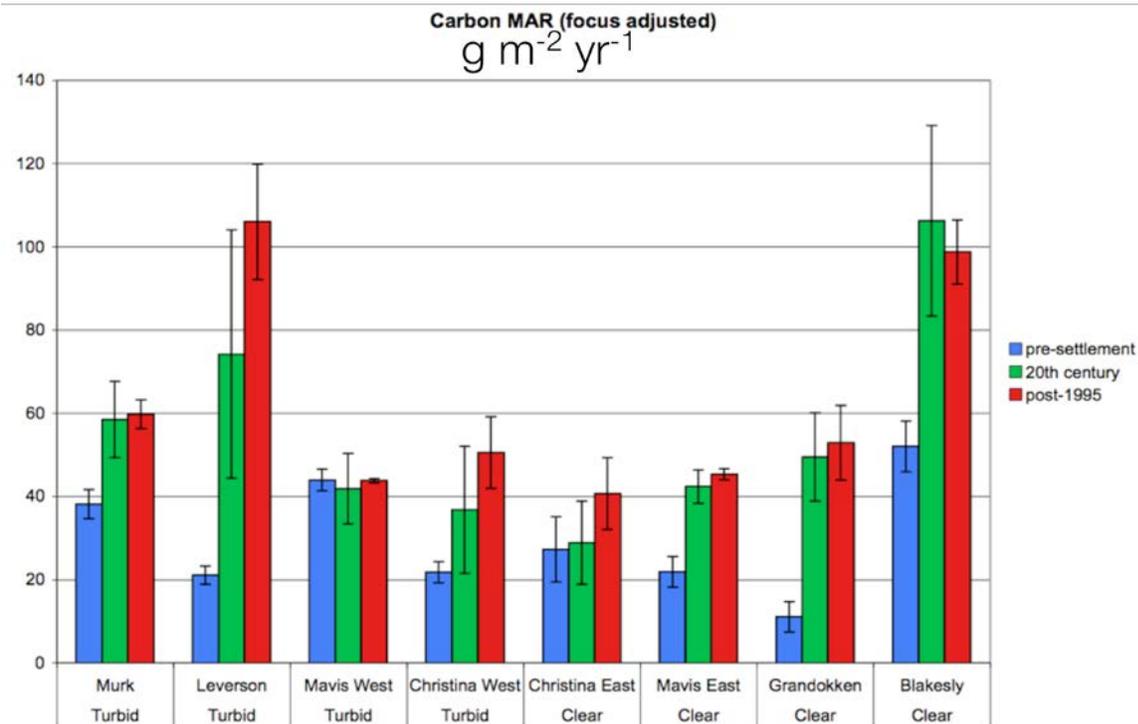


Fig. 3. Organic carbon burial rates in the western Minnesota ecoregion. Burial rates were estimated from dated (²¹⁰Pb) cores during different periods: pre-settlement (blue bars), 20th Century (green bars) and only in the last 15 years (red bars). These comparisons do not suggest that wetlands that are currently turbid (dominated by phytoplankton) or clear (dominated by macrophytes) bury organic carbon differently.

Minnesota (Fig. 3). We suspect that this increase is due to a number of factors but land clearing and more recently, intensive use of inorganic fertilizers are suspected to be important contributors. Also of note is the fact that clear (macrophyte-dominated) and turbid (phytoplankton-dominated) do not appear to differ significantly in the quantity of carbon buried, but it should be noted that we do not know how long these lakes have been in their current conditions, i.e., a lake that is presently turbid may have been clear in the past.

Result Status as of 31 December 2011:

We had hypothesized that dissolved oxygen exposure would be an important variable determining how much organic carbon is buried in the shallow lakes across the state. Therefore, we measured how far oxygen penetrates into sediments in each of the ecoregions as discussed above (in more than 70 lakes). Surprisingly, there was little variation in the depth to which oxygen penetrates (Fig. 4). But this does not necessarily

mean that the exposure time of oxygen does not have an effect on carbon burial rates because there could be significant variation in the exposure time due to differences in burial rates. Presently, we are continuing analyses of samples that were collected this past fall (measuring organic carbon content and ^{210}Pb) to better estimate burial rates. Subsequently we will model oxygen exposure times across the state to determine how large the differences are in the different eco-regions and if it matters to organic carbon burial.

The figure below shows the resolution and amount of data attained from each lake. Results showed that regardless of the location of the lake or the ecological regime it is currently in (turbid or clear water), the penetration of oxygen into the sediments was on average 3.6 ± 1.8 mm. Further data analysis is required to determine whether there are significant subtle differences amongst each of our study regions.

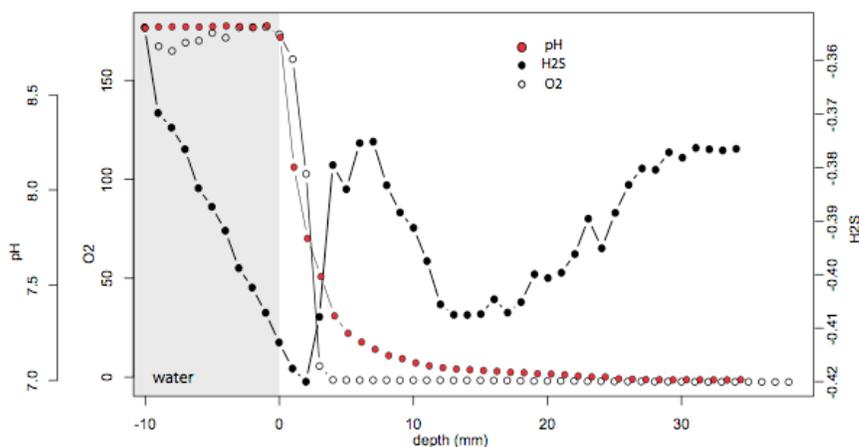


Figure 4: Lower Pigeon Lake in the Chippewa National Forest. Depth on the x-axis represents depth into the lake sediment, where 0 mm is the sediment-water interface. Oxygen is completely consumed by a depth of 2.5mm and pH decreases by over a unit and a half across the same interval.

Following the oxygen and pH measurements, the sediment cores were sub-sampled at 0.5 cm resolution in the field. Sediments were transported back to the University of Minnesota, weighed and freeze-dried, and dry bulk density was calculated for each interval. Currently, ~90% of the samples are dried and awaiting further analysis. Four undergraduate students working in co-PI Zimmer's lab have been pulverizing the sediment samples in preparation for elemental C and N analysis. Surface sediments from a subset of the lakes have been analyzed for ^{210}Pb activity, as a means to estimate the sediment accumulation rate in the lake using a model of radioactive decay. Currently, this approach is being refined, with scientists at the St. Croix Watershed Research Station, to enable us to estimate the sediment accumulation rate in each of our study lakes.

Result Status as of 30 June 2012:

All sediment samples have now been freeze-dried and sub-samples have been pulverized for the analysis of organic C. Pulverizing the samples ensures that a homogenous and accurate representative sample is taken. Hobbs (project post-doc) has now prepared (acidified and packed in analysis containers) a number of samples for each lake in order to show changes in the organic C concentration in the upper lake sediments (see Figure 5). This is important for the calculation of organic carbon burial rates. Samples are being analyzed in the lab of co-PI Zimmer and are near completion.

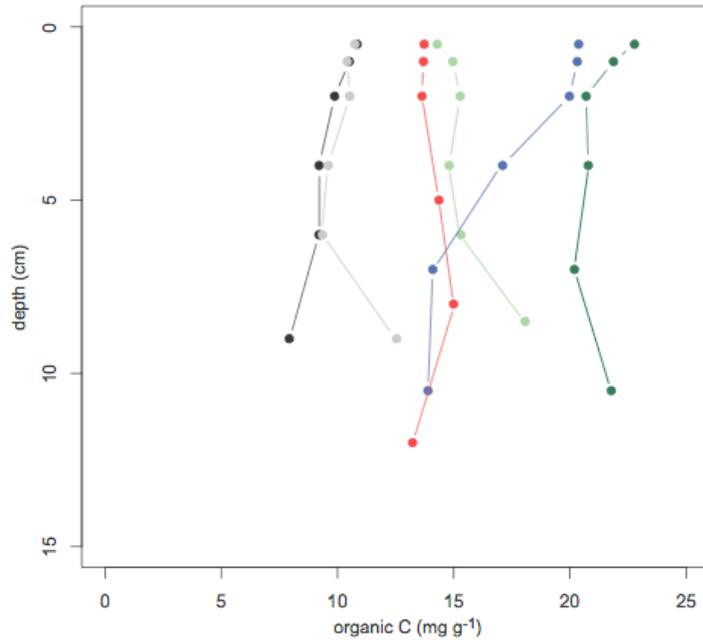


Figure 5: Organic C profiles in the surface sediments (0 cm being the sediment-water interface) from a number of lakes in western MN.

Additional samples will be analyzed to assure quality control

and accuracy of results. In order to estimate the rate of organic C deposition and burial in the lakes, a dataset of previously dated lake sediment cores from D.E. Engstrom (St. Croix Watershed Research Station) has been used to refine an accurate approach to using surface sediment radioisotopic lead activities as a means of assessing the modern (last 10 years) sedimentation rates for all 85 lakes in our dataset. This approach represents a significant advance in the science of dating and measuring lake sedimentation which will enable us to be able to estimate organic carbon burial much easier and in many more lakes. Composite sediment samples from each lake are now being compiled in order to incorporate the last 10 years of sedimentation. These composite samples will then be analyzed for lead activity and used in conjunction with the organic C concentrations to give a modern C-burial rate for each lake. Finally, the supplemental dataset of physical, biological, and chemical monitoring data for the lakes is near completion. This dataset will enable us to statistically compare the C-burial rates to a large number of lake variables to elucidate the dominant controls on C-burial.

Result Status as of 31 December 2012:

We have completed most of the sample collection and analyses and are in the process of synthesizing the analyses. As mentioned above, we have completed a manuscript describing a new method that we developed for estimating organic carbon burial rates from surface sediment samples and a manuscript describing this method has been submitted for publication (Figure 6). We will now apply this method to the 80 different lakes that we have samples from to estimate lake-specific organic carbon burial rates

and scale those results up for regional and state-wide estimates. In addition, the supplemental dataset of physical, biological, and chemical monitoring data for the lakes is completed so we will now be able to compare the C-burial rates to a large number of lake variables to elucidate the dominant controls on C-burial. This approach will allow us not only to understand these processes on a lake-by-lake and regional perspective, but by better understanding these mechanisms, we will be able to predict burial rates in many other lakes.

Result Status as of 30 June 2013: As discussed above, we have used this method for estimating burial to arrive at mean burial rates in shallow lakes that are about $120 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Figure 7). If we scale these measurements up to the entire state of Minnesota, it means that shallow lakes bury about 6 Tg (or 6 million metric tons) of carbon per year. This is about 4% of the total amount of carbon dioxide produced in the state per year through the burning of fossil fuels, not a huge percentage but it could nonetheless be managed in order to remove it more effectively. Some of our work also shows that low oxygen conditions may enable more effective carbon burial so that eutrophication of our freshwaters may enable more effective carbon burial. Although we do not advocate increased eutrophication of freshwaters, it is happening anyways, so this is one way where it may actually be a benefit.

Final Report Summary: 30 June 2013

We have found that shallow lakes bury organic carbon at very high rates compared to other landscape features. Effective burial is facilitated by high rates of productivity that occurs in these systems; anaerobic (no oxygen) conditions, when they occur, particularly in the winter time under the ice, also facilitates increased carbon burial. Although burial represents a large quantity of carbon, about 6 Tg per year (or 6 million metric tons), the State of Minnesota releases about 150 million metric tons of carbon per year through the burning of fossil fuels.

In addition to the scientific results of our work, this project has helped train numerous students (both undergraduate and graduate), technicians and post-doctoral fellows. Over 10 undergraduate students from both the University of St. Thomas and University of Minnesota were directly or indirectly (via funding for a related National Science Foundation project) supported on this project. Two graduate students at the University of Minnesota benefitted from this LCCMR project and the funding on this project supported a post-doctoral fellow for two years.

V. TOTAL ENRTF PROJECT BUDGET:

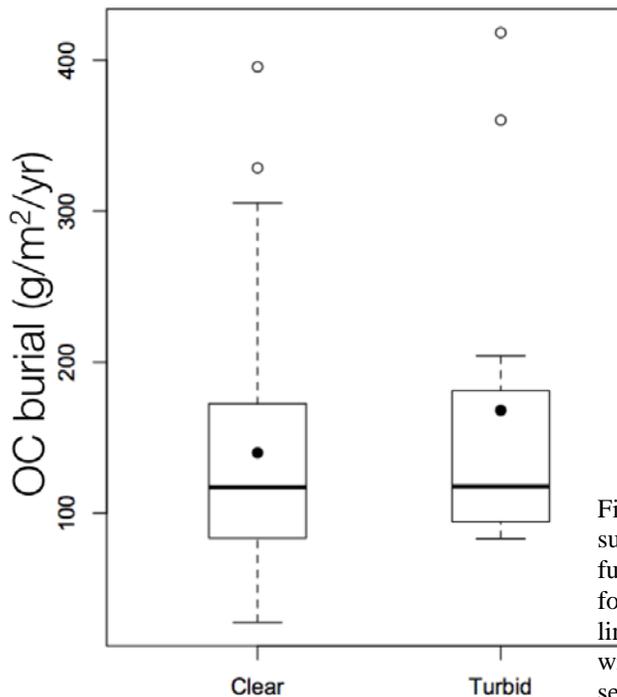


Figure 7. Median and variation (quartiles, mean and standard deviation) for organic carbon burial in shallow lakes throughout the state of Minnesota.

Personnel: \$ 115,425

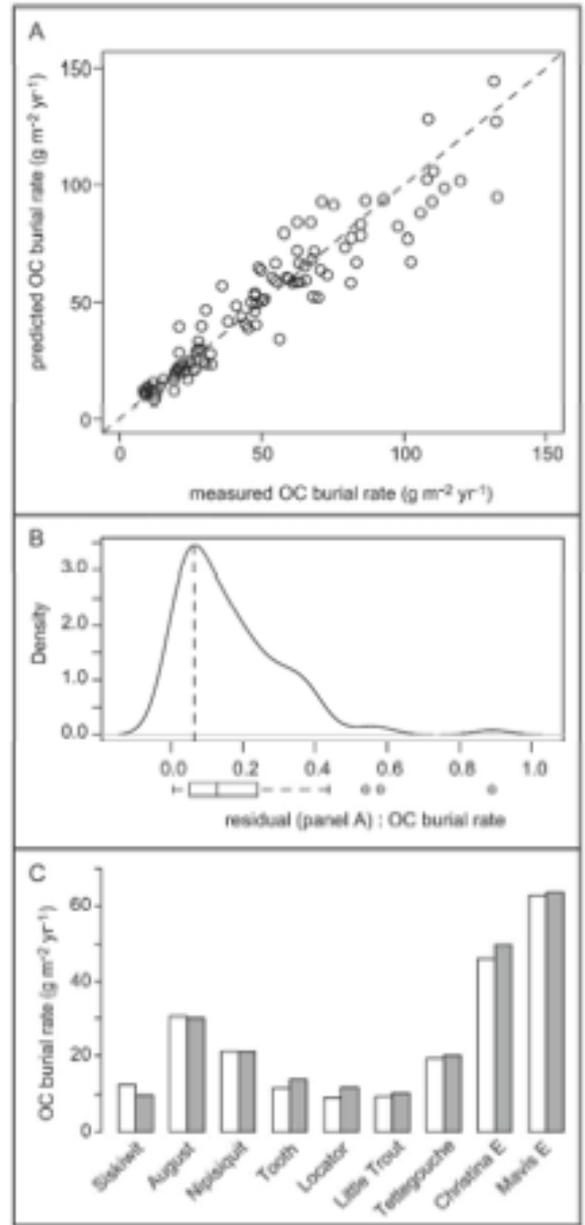


Figure 6. (A) Scatterplot of the estimated OC burial rates using the surface-sample approach against the measured values based on fully-dated cores over a 10-year period, adjusted for sediment focusing. (B) The density probability of the residuals from the 1:1 line of plot (A), expressed as a percentage of the measured value with the highest probable error shown as a dashed line. (C) Repeat sediment cores were collected and independently analyzed in 9 of the lakes (4 to 10 years apart); OC burial rates of the repeat samples (grey bars) are calculated using the surface-sample approach.

Post-doctoral fellow was paid 100% time to do the following: 1) Assess temporal variability in organic carbon burial rates in lake sediment cores taken throughout the state of Minnesota; 2) Assess variation in different regions of the state in terms of organic carbon burial; and 3) Determine the potential for carbon credits to be traded via a cap and trade system using Minnesota's shallow lakes.

Contracts: \$15,000

This funding was used to support Dr. Kyle Zimmer's (University of St. Thomas) efforts on the project. Most of this funding will support travel and supply expenses.

Equipment/Tools/Supplies: \$ 10,120

These funds were used primarily for supplies used in collection and processing of sample cores collected throughout the state of Minnesota. In addition to cores collected and processed for the NSF funded work, we collected cores and surface sediment samples from lakes in the other ecoregions (Figure 1). These funds enabled the collection, processing and analyses associated with these other regions such as: total organic carbon estimates and some stable isotope measurements.

Acquisition (Fee Title or Permanent Easements): \$

Travel: \$3,455

These funds were used to collect cores and surface sediment samples from shallow lakes throughout the state of Minnesota (Figure 1).

Additional Budget Items: \$

TOTAL ENRTF PROJECT BUDGET: \$144,000

Explanation of Capital Expenditures Greater Than \$3,500:

Although we did not have any capital expenditures in our original budget, we requested and got approval to purchase a microprobe system for measuring dissolved oxygen concentrations in sediments (see results in Fig. 4). The cost to this project was \$5,546 and the total cost of the instrument was approximately \$15,000, with one-third of the remaining cost coming from our NSF-supported work on mechanisms contributing to carbon burial in Minnesota shallow lakes and the other one-third coming from a colleague in University of Minnesota's Department of Ecology, Evolution and Behavior (Dr. Jacques Finlay) who also used this instrument.

VI. PROJECT STRATEGY:

A. Project Partners: Dr. Kyle Zimmer (University of St. Thomas: \$15,000)

B. Project Impact and Long-term Strategy: This work needed to be done to (a) help Minnesota take advantage of remaining wetlands in future carbon trading, and (b) to leverage funds to help protect those wetlands.

C. Other Funds Proposed to be Spent during the Project Period: National Science Foundation

\$443,474 to Cotner; Total award \$1,212,103. Clarification: There are five scientists from two universities (University of St. Thomas [including Zimmer] and University of Minnesota-Twin Cities), and one research institute (Science Museum of Minnesota/St. Croix Watershed Research Station) funded through this NSF project. Of the >\$1.2 million of total funding, Cotner received \$443,474 to fund research that was

related to, but not overlapping, with the work program outlined here. Much of the remaining work that is being funded by NSF is focused on interactions between climate variability and organic matter burial in the past. This work helped in the LCCMR project in that it helped us project organic matter burial in shallow lakes into the future.

D. Spending History: \$143,917

VII. DISSEMINATION: The results from this project have been incorporated into materials for use in the class room at St. Thomas and University of Minnesota. Cotner and Zimmer have used material from this project in lectures they have given locally, nationally and internationally (Sweden, Brazil, Japan). At the recent Ecological Society of America annual meeting, members of our team presented 11 posters and/or oral presentations that were very well received. We also organized a special session on terrestrial-aquatic linkages that had a strong focus on carbon burial. This was an extremely well-attended session at this international meeting. Also, 6 members of our group (Cotner, Zimmer, Hobbs and Ramstack-Hobbs, Herwig, and Hanson) presented results from this project at a Shallow Lakes Workshop that we helped organize in Fergus Falls this past August. This workshop was completely full and was attended by resource managers from throughout the state. Cotner has also been presenting some of this work through informal education talks that he has been giving in the past 18 months to various groups (mostly senior citizens) in the Twin Cities area. He has given approximately 20 presentations that have focused on marine and freshwater resources. Lastly, we have published three papers in the scientific literature based on results from this and a related project funded through the National Science Foundation. We have four other papers that are either currently being reviewed or that will be submitted by June 2014.

VIII. REPORTING REQUIREMENTS: Periodic work program progress reports will be submitted not later than 31 Dec 2010, 30 Jun 2011, 31 Dec 2011, 30 Jun 2012, 31 Dec 2012, 30 Jun 2013. A final work program report and associated products will be submitted between June 30 and August 1, 2013 as requested by the LCCMR.

Supplementary Documents:

We have included copies of two of the scientific papers that have been published from the results of this project.

Hobbs, WO, DR Engstrom, SP Scottler, KD Zimmer, and JB Cotner. "Estimating Modern Carbon Burial Rates in Lakes Using a Single Sediment Sample." LIMNOLOGY AND OCEANOGRAPHY-METHODS 11 (2013): doi:10.4319/lom.2013.11.316.

Theissen, Kevin M, William O Hobbs, Joy M Ramstack Hobbs, Kyle D Zimmer, Leah M Domine, James B Cotner, and Shinya Sugita. "The Altered Ecology of Lake Christina: A Record of Regime Shifts, Land-use Change, and Management From a Temperate Shallow Lake." Sci Total Environ 433 (2012): doi:10.1016/j.scitotenv.2012.06.068.

Final Attachment A: Budget Detail for 2010 Projects - Summary and a Budget page for each partner (if applicable)

Project Title: *Quantifying Carbon Burial in Healthy Minnesota Wetlands*

Project Manager Name: *James Cotner*

Trust Fund Appropriation: \$ 144,000

- 1) See list of non-eligible expenses, do not include any of these items in your budget sheet
- 2) Remove any budget item lines not applicable

2010 Trust Fund Budget	Revised Result 1 Budget: (05/19/2011)	Amount Spent or Encumbered (6/30/13)	Balance (6/30/13)	TOTAL BUDGET	TOTAL BALANCE
	<i>Estimate the statewide potential for shallow lakes to bury carbon in their sediments, and calculate the statewide potential for shallow lakes to serve as</i>	143,917	83	144,000	83
BUDGET ITEM					
PERSONNEL: wages and benefits					
Post-doctoral fellow (100% time for 2 years; 19% fringe benefits)	84,550	84,550	0	84,550	0
Technician (17% time for 3 years; 37% fringe benefits)	25,876	25,876	0	25,876	0
Undergraduate researchers	5,000	4,917	83	5,000	83
Contracts	15,000	15,000	0	15,000	0
Professional/technical					
Other contracts					
Other direct operating costs					
Non-capital Equipment / Tools					
Office equipment & computers - NOT ALLOWED unless unique to the project					
Capital equipment over \$3,500	5,546	5,546	0	5,546	0
Land acquisition					
Easement acquisition					
Professional Services for Acq.					
Printing					
Supplies (filters, lab chemicals for analyses and other supplies)	4,574	4,574	0	4,574	0
Travel expenses in Minnesota	3,454	3,454	0	3,454	0
Travel outside Minnesota					
Other					
Total	\$144,000	\$143,917	\$83	\$144,000	\$83