M.L. 2014 Project Abstract
For the Period Ending June 30, 2017

PROJECT TITLE: Watershed-Scale Monitoring of Long-Term Best-Management Practice Effectiveness

PROJECT MANAGER: Daniel R. Engstrom
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2014, Chp. 226, Sec. 2, Subd. 3(g)

APPROPRIATION AMOUNT: $ 900,000
AMOUNT SPENT: $ 900,000
AMOUNT REMAINING: $ 0

Overall Project Outcomes and Results

Nonpoint-source pollution (NPS) by sediment and nutrients represents the greatest human impact to Minnesota surface waters, especially in agricultural regions, yet monitoring records are too short to demonstrate the magnitude of the impact or potential benefits of best-management practices (BMPs). To fill this knowledge gap, our project used sediment cores, land-use compilations, and watershed modeling to reconstruct the long-term record of how land use has contributed to sediment and nutrient pollution in our rivers and lakes, and whether BMPs have been effective in reducing this pollution. Watershed erosion gradually fills in lakes over time, and so lake-sediment accumulation provides a record of watershed-scale erosion rates and changes.

We first re-analyzed statewide data from 142 lakes in our extensive lake-core archive. We then selected 14 lakes from the southern half of Minnesota for intensive analysis, collected 57 sediment cores from these lakes, and analyzed over 4,000 samples from these cores to determine the accumulation rates of sediment and phosphorus over the past 150 years. Radioisotope analysis determined the sediment age and source, whether from fields or stream channels. The results confirm that sediment erosion increased from the time of settlement in concert with increased cropland and the subsequent replacement of hay and small grains by corn and soybean row crops. In our intensive study lakes, sediment accumulation increased 2-10 (average 6) times over natural (pre-settlement) rates, and phosphorus accumulation increased 2-8 (average 5) times over natural rates. Radioisotopic fingerprinting indicated most of the lake sediment originated from fields, which is in contrast to our larger rivers such as the Minnesota, where bluffs and stream banks are the major erosion sources. Watershed modeling linked soil erosion to lake-sediment accumulation and confirmed that while BMPs produce beneficial results, they are overwhelmed by increases in row-crop acreage. We conclude that Minnesota needs to look beyond conventional BMPs towards putting more perennials in our croplands to achieve substantial water-quality improvement.

Project Results Use and Dissemination

Presentations have been given to the following groups in the Twin Cities and in out-state Minnesota: Clean Water Council; “Moving the Needle” taskforce to follow up on Governor Dayton’s Water Summit; Working Lands group, as organized by BWSR; Greater Blue Earth River Basin Alliance; Chippewa Watershed “10% Project”; Isaac Walton League (joint meeting for southern Minnesota chapters); Lake Pepin Legacy Alliance; Friends of the Mississippi River; Upper Mississippi River Conservation Alliance (in partnership with the U.S. Fish and Wildlife Service); Friends of the Star Prairie Land Preservation Trust; Great Lakes Protection Commission (national meeting). A special session is planned for this year’s Minnesota Water Conference on “The Need for and Potential of Creating Markets for BMPs” where project results will be discussed. Finally, a series of fact sheets will summarize the main components of the project for water-resource managers and an educated lay audience.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2014 Work Plan Final Report

Date of Report:	15 August 2017
Final Report	
Date of Work Plan Approval:	4 June 2014
Project Completion Date:	30 June 2017

PROJECT TITLE: **Watershed-Scale Monitoring of Long-Term Best-Management Practice Effectiveness**

Project Manager:	Daniel R. Engstrom
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Location: Statewide

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$ 900,000**
	Amount Spent:	**$ 900,000**
	Balance:	**$ 0**

Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 3(g)

Appropriation Language:
$900,000 the second year is from the trust fund to the Science Museum of Minnesota for the St. Croix Watershed Research Station to evaluate the effectiveness of best management practices in reducing sediment and nutrient loads at watershed scales over long time periods. This appropriation is available until June 30, 2017, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Watershed-Scale Monitoring of Long-Term Best-Management Practice Effectiveness

II. PROJECT STATEMENT:

Minnesota has widespread water-quality impairments due to nonpoint-source (NPS) pollution generated by agricultural, urban, and other human-altered lands. Mitigation of these impairments requires implementing best-management practices (BMPs) that are designed to limit soil erosion and nutrient transport from lands to receiving waters. Long-term data sets of water quality and land-use history are needed to tease apart the many factors that impact water quality. In particular, data sets that span periods before and after BMP implementation are needed to determine BMP effectiveness. However, such data sets are lacking, because water-quality monitoring of our lakes and rivers did not begin until well after humans altered the landscape. In this project, we will fill this data gap by constructing long-term water-quality records as preserved in lake sediments.

We will select five to ten lake basins in Minnesota for a detailed assessment of whole watershed loads of sediment and nutrients, as determined from multiple sediment cores collected from each lake. Our team of scientists will apply a comprehensive suite of proven analytical tools such as radioisotopic dating, sediment fingerprinting, algal analysis, and diatom reconstruction to determine the changes in pollutant loading over long periods of time, most critically before and after BMP implementation. In addition, our lab will bring a new capability to Minnesota by establishing the Center for Harmful Algal Research in Minnesota. The CHARM lab will use a specialized (inverted) microscope to identify algae in current noxious blooms and to develop novel techniques to document these blooms over time in the sediment record.

The chronology of these loads and blooms as determined from the sediment record will be compared against the history of land use and BMP implementation in each basin to search for statistical correlations. Finally, watershed computer models will be fit to these basins as constrained by the long-term data extracted from the sediment-core records, thereby both testing and improving the models. The benefits include development of critical long-term data sets, a test of BMP effectiveness at the watershed scale, and improvement of modeling tools to make results more realistic and predictive. These results will be transmitted to state and local resource managers in a series of workshops in the Twin Cities and in each study watershed. Fact sheets specific to each watershed will provide concise, easily understood results for local managers. The long-term data sets will greatly enhance the value of existing watershed monitoring in the state by providing temporal context, without which the current records are unanchored relative to natural, pre-industrial conditions.

III. PROJECT STATUS UPDATES:

Project Status as of 31 December 2014:

Four study watersheds were selected for Year 1 after consultation with state-agency colleagues and a systematic search through available spatial data sets. This search prioritized sites based on lake depth to assure a quality sediment record and on area of agriculture in the watershed to capture the impact of land use on lake water quality. So far 22 cores have been collected from this set of lakes. Analysis of these sediment cores has begun but is less than 5% complete.

In addition to these new sites, data analysis of 116 archived cores in the St. Croix Watershed Research Station database was undertaken to identify basic trends in watershed-scale soil erosion, as measured by lake-sediment accumulation rates (SARs). In agricultural watersheds, SARs have increased about five-fold since the time of Euro-American settlement. In forested watersheds, SARs have nearly doubled since the time of settlement, presumably from forestry and other human impacts, but remain far below SARs in agricultural watersheds. Watersheds with mixed land use have intermediate SARs that peaked in about 1960.

Project Status as of 30 June 2015:

Three more study watersheds were selected to complete Year 1, bringing our total to seven. These watersheds range greatly in size and were selected based on considering important watershed land-use changes that may have influenced the lake, and the potential quality of the lake-sediment record. So far we have 38 coring sites in these watersheds, plus nine deeper segments, for a total of 47. Most cores extend back in time to at least 1800 CE and some to before 1500 CE. Our fieldwork and coring is about 90% complete, and lab analyses about 20%. Annual harvested acreage since 1920 of all reported crops in the counties intersecting these watersheds was compiled to begin the baseline assessment of land cover in these watersheds. This compilation shows the chronology of how cropland has changed over the decades from a mix of corn, hay, and small grains to the bi-culture of corn and soybeans today.

Amendment Request (24 August 2015):

We request a change in the budget for Activity 2. We had originally planned on submitting sediment material for radiocarbon (C-14) dating through the University of Minnesota. However, for our sediment cores this requires selecting microscopic pieces of charcoal for analysis, and colleagues at St. Olaf College were better poised to accomplish this task, at the same cost.

Amendment Approved by LCCMR 8-28-2015

Project Status as of 31 December 2015:

With the addition of two more sites during the present reporting period, nine watersheds have been finalized as our study units, with a principal lake in each watershed and a subsidiary lake in three of them. A total of 52 core segments have been collected from these lakes to document the environmental histories of these watersheds. Analysis of these cores is currently about 60% complete. New methods of analyzing phosphorus in cores have been implemented and refined, which has shed light on phosphorus mobility in cores and its potential to contribute to algal productivity in lakes. Geographic information system (GIS) data are being compiled to characterize each watershed and to help develop statistical relations to the lake-sediment data. These data include land cover (cropping histories), tillage transect summaries, and land enrolled in conservation programs (i.e., CRP, CREP, and RIM). An inverted microscope has been purchased and installed, which will allow identification of algal assemblages from both modern water samples and from subfossil remains found in lake sediment. Installation of this microscope is the first step in building the CHARM lab -- the Center for Harmful Algal Research in Minnesota. As of 31 December 2015, the project reached the half-way point of its timeline, with 40% of the funds expended.

Amendment Request (13 May 2016):
We request a change in the budget to allow for more detailed analyses of sediment phosphorus. Current literature indicates that new extraction methods may be helpful in characterizing different phosphorus fractions in soils and sediment, and we plan to adapt these methods to our sediment phosphorus samples, thereby increasing the funds to be spent for Activity 2. These additional lab analyses will require extra lab supplies ($16,000) and extra analyses performed through the University of Minnesota ($34,000). To pay for the lab supplies, we request to shift funds originally budgeted for travel in Activities 1, 2, and 4. We saved considerable travel monies during fieldwork by avoiding overnight stays in most cases. To pay for the extra phosphorus analyses, we request to reduce the salary line in Activity 3 from $294,000 to $260,000. While this will reduce the funding available for statistical analyses and watershed modeling, we can economize there by prioritizing our watersheds according to the sediment-data quality and reducing modeling detail for the lower priority sites.
Amendment Approved by LCCMR 5/11/2016

Project Status as of 30 June 2016:
Two more lake sites in Glacial Lakes State Park (Pope County) were added for study, bringing our lake total to 14 and our sediment core total to 57. These last two sites provide an important end member for our study because although they lie in an agricultural region, their local watersheds are native prairie with no tillage and minimal grazing. Geographic information system (GIS) characterization of lake watersheds is complete, with cropping histories and best-management practice histories compiled, along with crop acreage within 50-500 feet of principal streams leading to the study lakes. Laboratory analyses of lake sediment cores is about 80% complete overall, including analysis of major components (organic, inorganic, and carbonate matter), radiometric dating, sediment phosphorus, and biogenic silica. Analysis of algal pigments and diatoms awaits. Watershed modeling with the Soil and Water Assessment Tool (SWAT) has begun with the Pomme de Terre River watershed in western Minnesota, wherein lie several of our study lakes (Barrett and Perkins). The model will provide a measure of landscape-scale erosion and nutrient transport that is independent from the estimate provided by the sediment cores. Reconciliation of the two independent measures will improve accuracy of results and provide a mechanistic link between land use in the watershed and impacts on the study lakes. As of 30 June 2016, the project has reached the two-thirds point in its timeline, with 63% of the funds spent.

Project Status as of 31 December 2016:
All fieldwork and nearly all lab work have now been completed on this project. We are awaiting a few lake-sediment analyses from external labs (algal pigments and ^{10}Be), but the most critical analyses (radioisotopic sediment chronologies, sediment components, and nutrients) are complete. For each of our primary study lakes, the time series of annual sediment accumulation rates from multiple cores have been integrated into a single master time series averaged for the entire lake. Likewise, watershed characterization also has been completed, allowing us to directly compare cropping histories, BMP implementations, and lake sediment records in our study watersheds. These comparisons will serve to generate hypotheses about the main influences on the watershed erosion rates. We are using watershed models to test these hypotheses, and models have been constructed for both the Pomme de Terre watershed (comprising Barrett and Perkins lakes) and the Solem Lake watershed. Preliminary results suggest that although many lands have been enrolled in conservation set-aside programs (e.g., CRP), acreage of row crops remains high in conjunction with high lake-sediment accumulation rates, as a proxy for watershed-scale soil erosion. Watershed modeling is helping to parse the relative influence of cropping areas, BMP practices, and rainfall patterns on watershed erosion in an effort to mechanistically link the land-management history to the lake-sediment record. As of 31 December 2016, the project has reached 83% of its timeline, with 78% of the funds spent.

Amendment Request (26 April 2017):
As this project winds down, we request a change in the budget to allow for final course corrections. In round numbers, we will have about $8,000 in savings from reduced supplies expenses, and phosphorus analyses were about $5,000 less than expected. The largest change has occurred because of an analytical delay in the Utah

State Laboratory, which has been unable to process about $20,000 of planned ^{10}Be analyses. We would like to use part of this savings (about $3,000) to fund additional ^{210}Pb dating to improve the temporal resolution of our sediment cores. But mostly we propose to increase the time spent on modeling and data analysis ($30,000), which has proven to be more time consuming than anticipated. We have new hydrological modeling capabilities to apply more highly detailed runoff models that leverage the use of LiDAR data sets, which should help the land-lake linkage in small watersheds.
Amendment Approved by LCCMR 4/27/2017

Overall Project Outcomes and Results:
Nonpoint-source pollution (NPS) by sediment and nutrients causes the greatest impact to Minnesota waterways, especially in agricultural regions, yet stream-monitoring records are too short to demonstrate the magnitude of the impact or potential benefits of best-management practices (BMPs). To fill this knowledge gap, our project used lake-sediment analysis, land-use compilations, and watershed modeling to construct the long-term record of how land use has caused NPS sediment and nutrient pollution in our rivers and lakes, and whether BMPs have been effective in reducing this pollution. Soil erosion gradually fills in lakes year by year, and so lake-sediment accumulation is a record of watershed-scale soil erosion. We first re-analyzed statewide data from 142 lakes in our unique lake-sediment archive. Given this context, we selected 14 lakes from the southern half of Minnesota for intensive analysis, collected 57 sediment cores from these lakes, and analyzed over 4,000 sediment samples from these cores to determine the accumulation rates of sediment and phosphorus over the past 150 years. Radioisotope analysis determined the sediment age and source, whether from fields or stream banks. The results confirm that soil erosion increased from the time of settlement in concert with increased cropland and has continued to increase as hay and small grains have been replaced by corn and soybean row crops. In our intensive study lakes, sediment accumulation increased 2-10 (average 6) times over natural (pre-settlement) rates, and phosphorus accumulation in the sediment increased 2-8 (average 5) times over natural rates. Radioisotopic fingerprinting indicated most of the lake sediment originated from fields rather than stream banks. Watershed modeling linked soil erosion to lake-sediment accumulation and confirmed that while BMPs produce beneficial results, they are overwhelmed by increases in row-crop acreage. We conclude that we need to look beyond conventional BMPs towards putting more perennials in our croplands to achieve substantial water-quality improvement.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Select new sites, characterize watersheds, & document BMP histories

Description: A careful selection of study sites will be critical to the success of this research effort. Each selected watershed will encompass a *principal* lake that receives runoff (and likely also groundwater and tile flow when present) that delivers loads of sediment and nutrients to the lake. The watershed may also contain *subsidiary* lakes or ponds where additional information may be gathered regarding effects of local practices or issues of scale. Our selection strategy will focus on sites representing a range of land-use change and BMP implementation, and those sites likely to possess high-quality sediment records. To help in this regard, we will sift through the SCWRS state-wide archive of over 100 radiometrically dated lake-sediment cores to identify trends in siliciclastic sediment accumulation rates, and thus erosion rates, over the last century. Watershed-scale erosion rates will be statistically summarized by ecoregion or other selected data subsets to provide a foundation for selecting representative sites for the detailed analyses to follow. We will also meet with state agency and university personnel involved with current monitoring, modeling, and benchmark-site programs (e.g., the sentinel lake and watershed projects) to consider sites where efforts may be synergistic. Armed with this background and depending on watershed size and complexity, we will select five to ten lake watersheds for detailed study.

For selected watersheds, geographic data will be compiled and summarized. These data sets will be key for Activity 3 where they will be used for correlation to long-term sediment-core data and for input to the watershed models. Hydrographic and topographic data sets are readily available. Hydrologically conditioned DEMs (based on 10-m grids or LiDAR if available) will be used to generate flow-length grids (distance between the grid cell and receiving water), thereby providing a measure of hydrologic proximity useful for weighting BMP impact. Soils data will be obtained from the SSURGO database. The more difficult data to compile will be land-use and BMP histories. Recent land cover is available as spatially referenced data sets (i.e., GIS layers) based on satellite imagery, namely the National Land Cover Dataset (NLCD) and U.S. Department of Agriculture Crop Data Layer (CDL) dataset. Because these spatial data sets are not entirely comparable to each other and because they begin in about 1992, we will use tabular data from the USDA to enforce consistency for cropland areas and to extend the data back to the early 1900s. Land-use practices on agricultural lands will be assessed from a variety of sources, including tillage transect data and local information from county soil and water conservation district (SWCD) offices, statewide databases tracking BMP implementation (e.g., BWSR e-link conservation database), and federal data on conservation practices and land retirement. Data generated for the Conservation Effects Assessment Project (CEAP) will be queried to the degree available. We already possess snapshots of land polygons in the Conservation Reserve Program (CRP) in Minnesota for the 1990s and 2000s. Land-cover, land-use, and BMP histories will be aggregated into time slices corresponding to those available in the sediment core records, probably decadal resolution back to about 1930 and multi-decadal prior to that.

Summary Budget Information for Activity 1: **ENRTF Budget: $ 136.000**
Amount Spent: $ 136,000
Balance: $ 0

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. Analyze existing data for 100+ lakes in SCWRS database; select 5-10 lake watersheds for complete analyses during this project	Jun 2015	$ 38,500
2. Compile geographic, climatic, land-use, and BMP data for selected watersheds	Dec 2015	$ 97,500

Activity Status as of 31 December 2014:

Our site selection process intersected (a) the site characteristics targeted by our project, (b) sites targeted by other projects complementary to ours, and (c) available data sets to screen potential sites. Our project seeks to find relatively deep lakes with good sediment records in with watersheds that have been significantly impacted by agricultural land use. We met with agency and university staff regarding the Sentinel Lakes and Sentinel Watersheds projects to identify their priorities and key sites. While there is some overlap between projects, many of the Sentinel Lakes are somewhat protected from land-use impacts and hence not ideal for our project, and many Sentinel Watersheds do not have lakes in strategic locations. Nonetheless the shared data from these projects have been useful in identifying deeper lakes with some potential for our purposes, and in summarizing data availability for many potential sites.

Our next step was to prioritize potential study sites with a systematic statewide search of existing spatially referenced (geographic information system, or GIS) data sets. We started with a data set of 3,774 lakes with known depths and areas, built from several data sets provided by the MDNR. We prioritized these lakes according to a simple numerical ranking index based on (a) being deep enough to have a reliable sediment record (> 4 m deep), and (b) having a large watershed in row crops to maximize potential for land-use impact and possible remediation from establishment of best-management practices (BMPs). From this prioritized list, we then systematically searched through physical maps to find suitable sites. We found it surprisingly difficult to select sites that ideally satisfied our criteria. Many lakes that ranked highly with our simple index were too small to characterize a significant part of the landscape. Many of the larger and deeper lakes were buffered by upstream lakes and wetlands that would interfere with the signal of land-use change as recorded in the lake sediment. Consequently significant professional judgment and experience were needed for final site selection. So far we have settled on two lake watersheds in the Minnesota basin (Barrett and Miller), one in the Crow basin (Richardson), and one in the St. Croix basin (Cedar) (Fig. 1). The remaining sites will be chosen later this winter after further consideration.

In addition to these new sites, our database of many other lakes cored in Minnesota was analyzed to identify both spatial and temporal trends in inorganic sediment accumulation rates, as a proxy for watershed-scale soil erosion. This analysis has provided a regional, long-term context for our newly selected study sites. The 116 lakes analyzed in this database span the major ecoregions of Minnesota, from the northern lakes and forests (NLF) in the north and east parts of the state to the western corn-belt plains and northern glaciated plains (WCBP and NGP) in the south and west (Fig. 1). Intermediate to these ecoregions is the north central hardwood forest (NCHF), which runs diagonally across the state from northwest to the southeast. Lake sediment chronologies were determined with standard radiometric techniques (^{210}Pb and ^{137}Cs), and sediment content was determined by loss-on-ignition methods. The eroded soil content of lake sediment is fundamentally that which remains after heating the sediment to 1000 deg C, which drives off all organics and carbonates, leaving behind mostly siliciclastic matter. In this report, the sediment accumulation rate (SAR) refers to the mass of eroded soil deposited in a lake per unit area of lake bed each year (grams per square meter per year, or g m^{-2} yr^{-1}).

Soil erosion, and its consequent impact on aquatic resources, has unquestionably been driven by human land-use practices since the time of Euro-American settlement in the early 1800s (Fig. 2). Widespread and intensive logging disturbed lands throughout the NLF ecoregion, while near-total conversion of tallgrass prairie into farmland, combined with substantial wetland drainage, has created human-dominated agroecosystems in the WCBP and NGP ecoregions. Modern sediment accumulation rates (SARs) are greatest in lakes located within watersheds dominated by agricultural land uses (median 470 g m^{-2} yr^{-1}, n=27) and lowest in northern forest lakes (median 77 g m^{-2} yr^{-1}, n=54). Lakes in watersheds characterized by urban or mixed land uses in the central portion of the state show intermediate SARs (median 123 g m^{-2} yr^{-1}, n=35) that peaked in about 1960. In all but 9 lakes, SARs have increased above natural background rates (pre-settlement). SARs have approximately doubled in the northern forested lakes but have not begun to return toward pre-settlement levels, perhaps due to legacy impacts from prior logging. In the agricultural lakes, SARs have increased more than fivefold. Accumulation rates climbed sharply during initial land clearance and early farming, but increases after ~1940 appear to be somewhat diminished. If the small changes in the curve are meaningful, it is possible that SARs in agriculturally dominated lakes have leveled off in the last 30 years (see Fig.2), perhaps as a result of improved agricultural methods to reduce soil erosion. Nonetheless, rates remain far above natural levels.

Activity Status as of 30 June 2015:
Site selection continued after analysis of reconnaissance cores collected during the previous reporting period. In addition to the four watersheds selected in late 2014, we are adding another three from west-central and southern Minnesota: Kansas, South Heron, and Solem (Fig. 1). It is possible that problems in radiometric dating of sediment will make one or more of these sites unusable, but if so we have several alternative sites lined up. Big Elk Lake, cored during a previous study, may be added and cored again for additional data reliability. Another alternative would be the Cannon River watershed, from which we plan to take reconnaissance lake cores later this summer. Given the lake sites already cored and potential sites already selected, this outcome of Activity 1 is very nearly complete.

We continued work on compiling geographic and land-use data on our study sites (Outcome 2 of Activity 1). The main activity was compilation of county-wide cropping patterns for the state, based on annual surveys published by the National Agricultural Statistics Service (NASS). Figure 3 shows patterns from Carver and Grant counties, which correspond to our Miller Lake and Barrett Lake sites, respectively (see Fig. 1 for locations). Carver County, in the eastern part of the state, shows a slow but relatively steady increase in corn acreage since 1920. At least until about 1960, the acreages of corn, hay, and small grains were co-equal. Soybeans started in about 1960 but began a major increase after about 1980. As a consequence, small grains were pinched out and hay gradually declined as well, until by about 2010 virtually all fields were corn or soybeans. In Grant County, in the western part of the state, small grains were dominant over much of the period from 1920 to 1980. These were principally barley and oats until about 1970, and thereafter replaced mostly with wheat, with significant acreage through the mid-1990s. However, the rapid increase of both corn and soybeans starting in about 1980 resulted in the loss of wheat, and by 2010 or so, just as in Carver County, nearly all the fields became corn or soybeans.

Activity Status as of 31 December 2015:
Site selection has been finalized, with the addition of Big Elk Lake (Sherburne County) as our final study site (Fig. 1). This brings our total number of lake sites up to 12, with nine principal lakes and three subsidiary lakes. Watersheds will be characterized for the nine principal lakes; the subsidiary lakes lie within the watershed of the nearest principal lake. Data from our existing archives of lake sediment from over 100 Minnesota lakes have been further analyzed to better characterize watershed impacts on lake histories over the past 200 years. Organic matter accumulation, as a proxy of lake productivity, has been documented, as well as inorganic matter accumulation, as a proxy of whole-watershed erosion rates (Fig. 2). Hence Outcome 1 of Activity 1 is essentially complete, except for report preparation of the results.

Watershed characterization (Activity 1, Outcome 2) continued. In addition to cropping history data back to 1920 (Fig. 3), tillage transect data (1990-2007) and conservation grasslands data were compiled. The conservation grasslands data include results of several federal and state set-aside programs: Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), and Reinvest in Minnesota (RIM). Fig. 4 shows the placement of Conservation Reserve Program (CRP) grasslands in the watershed of Richardson and Dunns lakes, in Meeker County. Riparian buffer quality (i.e., land not in row crops within 200 and 500 feet of perennial watercourses) are currently being analyzed for study watersheds. Now that fieldwork and labwork are winding down, work on watershed characterization will become more focused during the first half of 2016.

Activity Status as of 30 June 2016:
Two more lakes, studied initially as part of another project, were added to our data set for this project: Baby and Mountain lakes, in Pope County, located in Glacial Lakes State Park (Fig. 1) and thus protected since at least 1963 when the park was established. Because these lakes lie in native prairie without significant agricultural activity (i.e., no tillage and minimal grazing) they form an important end member in our analysis of land-use

impacts on lakes. This brings our lake total up to 14. These latest lake additions to our total data set mark the completion of Activity 1, Outcome 1.

Watershed characterization continued with the characterization of row-crop and perennial vegetation within corridor widths of 50, 100, and 500 feet of the main stream channel leading to each lake (for those lakes with an inlet). No one should be surprised that agricultural land is common within 500 feet of a stream: percent areal coverage ranged from 13 to 77%, with a median of 51%. But even within 50 feet of the stream, the median areal coverage was 32%, and as high as 67% in one of our watersheds. Buffer characterization marks the completion of Activity 1, Outcome 2.

Activity Status as of 31 December 2016:
Watershed characterization has been completed for 12 of the 14 lakes included as part of this study (all cored primary lakes exclusive of the two subsidiary lakes, Perkins and Flaherty). This represents the completion of this phase of the project as these are the 12 lakes for which changes in watershed characteristics (cropping patterns, conservation tillage, BMP lands, stream buffering) will be compared to watershed erosion rates derived from multi-core averages. This correlative analysis (Activity 3, Outcome 1) will serve as a hypothesis generator for the primary drivers in watershed erosion rates that can then be mechanistically tested through our watershed modeling efforts (Activity 3, Outcome 2).

Final Report Summary:
To give the “big picture” of how land use influences soil erosion and thus lake-sediment accumulation, we re-analyzed data from 142 lakes from across the state, for which we have lake sediment stored in our unique lake-sediment archives at the St. Croix Watershed Research Station. This re-analysis (Fig. 13) provided important temporal and spatial context for detailed study of sites selected for the present study, and updates an earlier effort with 116 lakes (Fig. 2). Here, we refer only to the accumulation of siliciclastic inorganic lake sediment, i.e., eroded soil particles excluding any organic or carbonate matter. Lakes in agricultural watersheds had a dramatic increase in sediment accumulation starting at the time of settlement (~1850) and escalating after 1900, in concert with the increasing area of farms and cropland (Fig. 13a & b) that increased soil erosion. Even though cropland has remained high and constant since about 1940, lake sediment accumulation declined for a few decades (1940-70), perhaps in response to soil conservation efforts begun during the Dust Bowl era. Nonetheless, after 1970 lake sediment accumulation (and thus erosion) rose again to new heights, as agriculture marched towards a simple corn-soybean dominance in which fencerows were removed, small grains and forage crops declined, and tile drainage exploded. Precipitation in Minnesota has generally increased since about 1930 (Fig. 14), which in combination with tile drainage has shunted more water into rivers and streams. These increased flows cause bank and bluff erosion, which adds to the soil erosion getting into our waterways, and thereby explaining the very high lake-sediment accumulation rates of today in agricultural lakes. Today’s agricultural BMPs, such as conservation tillage, buffer strips, and land retirement, no doubt have locally reduced nonpoint-source (NPS) loads of sediment and nutrients. However, on a statewide scale the dominance of large-scale corn-soybean agriculture has simply overwhelmed these BMP efforts. While the BMPs may have kept NPS loads from being larger, they have not reduced them.

Lakes in urban/mixed land use likewise show a rise in sediment accumulation rates (and thus watershed-scale erosion) since the time of settlement and escalating after 1900 (Fig. 13a). However, rates declined after about 1970, presumably as agriculture gave way to suburbanization, where lawns and impervious surfaces replaced tilled cropland. Still rates remain much higher than natural. Lakes in undeveloped watersheds, largely in the northern forest regions but also including a few prairie preserves, have been impacted to a much lesser degree by logging and rural residential growth. We hypothesize that some of this post-settlement lake-sediment accumulation in undeveloped lakes may be from dustfall arising from agricultural lands far to the west, because even lakes in protected wilderness areas without any local land-use impacts appear to have sediment accumulation rates elevated above natural background rates.

Following this statewide analysis, we created systematic search criteria to select a small set of lakes for detailed study. Starting with a GIS database of 3,774 lakes with known depths and areas, we created a prioritization index to rank lakes that were deep and surrounded by cropland. Specifically, we aimed for lakes that (a) were deep enough (>4 m) to have not dried out in the 1930s (or earlier) and thus likely to have a good sedimentary record, and (b) had substantial row-crop agriculture in their watersheds to maximize potential for land-use impact and possible remediation from establishment of best-management practices (BMPs). From this prioritized list, we then systematically searched through physical maps to find suitable sites. We found it surprisingly difficult to select sites that ideally satisfied our simple criteria. Many lakes that ranked highly with our simple index were too small to characterize a significant part of the landscape. Many of the larger and deeper lakes were buffered by upstream lakes and wetlands that would interfere with the signal of land-use change as recorded in the lake sediment. Consequently significant professional judgment and experience were needed for final site selection. We settled on 12 primary study lakes and watersheds (Fig. 1); about half were chosen the first year and half the second year. In addition, we selected two subsidiary lakes, within the watersheds of two of the primary lakes, for further data about scaling within nested subbasins.

The watersheds of all 12 primary lakes were characterized for cropping history (land use) and best management practices (BMPs). County cropping data going back to 1920 were compiled and distributed to each of the study watersheds. Fig. 3 shows examples from Carver and Grant counties, showing how small grains and forage crops have drastically declined because of a near dominance of corn and soybeans. Three measures of BMPs were compiled. First, the amount of buffered waterways was estimated by characterizing the relative proportion of row-crop versus perennial vegetation within corridor widths of 50, 100, and 500 feet of the channel centerline of the main streams leading to each lake. Not surprisingly, agricultural land is common within 500 feet of a stream: percent areal coverage ranged from 13 to 77%, with a median of 51%. But even within 50 feet of the stream, the median areal coverage was 32%, and as high as 67% in one of our watersheds. Second, the relative proportions of different tillage practices (intensive, conservation, and no-till) were compiled for each county based on tillage transect data from 1990-2007 and distributed to each of the study watersheds. Third, the areas of conservation grasslands (set-aside or retired lands such as CRP, CREP, and RIM) were likewise compiled for each watershed (e.g., Fig. 4).

ACTIVITY 2: Collect and analyze lake-sediment cores

Description: A main objective of lake-sediment collection and analysis is to measure the total amount of fine-grained sediment and nutrients trapped by each principal lake and to determine the timing (chronology) of when this occurred. Only by knowing the total amounts (and not just relative changes over time) can the loads be quantitatively related to whole-watershed erosion and nutrient loss rates from the surrounding landscape. Multiple sediment cores from different points in each lake are the most reliable method to measure whole-lake accumulation, so we will collect three to eight cores from each principal lake, depending on the complexity of the lake morphometry. In addition, should subsidiary lakes or ponds be present elsewhere within the watershed of a principal lake, sediment cores will be collected from a subset of these lakes to help resolve issues of transport and scale.

Not all cores will receive equal treatment. Central, primary cores from each principal lake will be analyzed for all the analyses listed below. Secondary cores from more peripheral parts of each principal lake will be analyzed for a reduced set (major sediment components and nutrients) and dated as necessary to achieve a correlative chronology with the primary core. Tertiary cores will be taken and interpreted in the field to identify the depositional area within each lake, with lab analysis limited to simple sediment content at most. Cores from subsidiary lakes will be treated as secondary cores with a subset of analyses selected specific to that watershed, depending on the question they are helping to answer. Considering all primary, secondary, and tertiary cores from both principal and subsidiary lakes, we expect to collect a total of 50-60 cores.

To obtain the sediment chronology, cores will be radiometrically dated by ^{210}Pb methods, supplemented as needed by identifying the 1963 ^{137}Cs peak that is remnant from the atmospheric testing of nuclear bombs. Based on typical sediment accumulation rates in Minnesota lakes, it should be possible to obtain reliable dates back to the mid to early 1800s in all lakes. Dating resolution will be roughly decadal. Older material in selected lakes will be dated by ^{14}C to assess natural background sediment accumulation rates.

Sediment cores will be analyzed for a suite of components to assess the loads of sediment and nutrients, as a reflection of the water quality of the runoff (and other hydrologic components) reaching the lake. Loss on ignition analysis will determine organic, carbonate, and siliciclastic (eroded soil) components. Surface-fallout radioisotopes (^{210}Pb, ^{137}Cs, and ^{10}Be) will be used to fingerprint the sediment according to its origin, namely, a mixture of field and non-field sources. Phosphorus content (both total and extractable fractions) of the sediment will determine apparent loads of this essential nutrient. In concert with sediment phosphorus, lake-water phosphorus content over time will be estimated by analysis of the remains of diatoms, a group of algae with certain species that are diagnostic of phosphorus content the water in which they live. General algal productivity will be assessed by the accumulation of biogenic silica, which is largely composed of the glass cell walls of these diatoms. Fossil pigments will also be analyzed, which can diagnose presence of blue-green algae, generally considered indicative of noxious conditions.

A new addition to our toolbox will be the analysis of soft-body subfossil algal remains in sediment. This analysis requires a distinctive type of microscope, an “inverted” microscope, to allow identification of algal parts that have settled in a shallow well in specialized slides. The same equipment and procedure can also be used on fresh samples of algae as well, giving our lab the capability of providing community analysis of existing algal blooms. With the acquisition of this new microscope, we expect our lab to become a resource for agencies and other institutions needing to identify the species composition of noxious algal blooms. We have named this resource the CHARM lab—the Center for Harmful Algae Research in Minnesota.

Summary Budget Information for Activity 2: **ENRTF Budget: $ 423,229**
Amount Spent: $ 423,229
Balance: $ 0

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. Collect and analyze 3-8 sediment cores per lake	Sep 2016	$ 375,229
2. Establish Center for Harmful Algae Research in Minnesota (CHARM lab)	Jun 2015	$ 48,000

Activity Status as of 31 December 2014:
Four coring trips were undertaken during the reporting period. These included Barrett Lake in the western Minnesota River basin (4 cores); Richardson and Dunns lakes in the Crow River basin (8 cores); Cedar Lake in the St. Croix River basin (6 cores); and Dead Coon, Kansas, South Heron, and Fish lakes in or near the southwestern Minnesota River basin (4 cores). The last trip was reconnaissance to explore which of these lakes may be worthy for a more detailed analysis with multiple cores. We are planning on coring Miller Lake, in the eastern Minnesota River basin, this winter through the ice. The current core total stands at 22; Miller Lake will add another seven.

Lab work has proceeded on the cores at a steady pace since their collection. All cores have had initial magnetic scans, and most have been sectioned, with subsamples extracted for algal and pigment analyses (to be done later). Loss-on-ignition analysis (to determine basic sediment content, including eroded soil content) has been completed on 8 cores, and ^{210}Pb analysis (to determine sediment chronology) has been completed on 5 cores.

Activity Status as of 30 June 2015:
Three more coring trips were taken during this reporting period. Multiple cores were collected through the ice from Miller Lake (Carver County) in January, and from South Heron and Flahtery lakes (Jackson County) in March. After ice out, cores were collected via boat from Solem Lake (Douglas County) and Perkins Lake (Stevens County). The current core total includes 38 surface cores, plus 9 deeper core segments, for a total of 47. Further cores from Kansas Lake and perhaps from the Cannon River chain would bring our core total well within the target range of 50-60.

Lab analysis has proceeded steadily. All cores have been analyzed for magnetics, and only the cores from Solem Lake await sectioning, subsampling, and basic processing for further analysis. The most critical initial analysis is to obtain a good sediment chronology -- everything else depends on this. Good sediment dates are imperative (a) to correlate known events in the watersheds with their expression in the sediment core, and (b) to calculate rates of sediment accumulation, with give us a whole-watershed estimate of landscape erosion. Our principal tool is lead-210 analysis which can give a chronology back to about 1850 CE; 17 cores have been dated so far. To refine the lead-210 dates, we use the peak in cesium-137, which marks 1963 CE, the end of atmospheric nuclear testing. So far nine cores have been checked for cesium-137. To extend our time window to before 1850 AD, carbon-14 will be analyzed on selected primary cores to allow estimates of natural (pre-Euroamerican settlement) rates of sediment accumulation. Currently samples are being prepared from four lakes for carbon-14 analysis, which we estimate will extend our sediment chronology back to at least 1500 CE.

Following the establishment of good sediment chronologies, the next steps are the analysis of core contents to identify which components have changed over time. To explore nutrient loads over time, sediment phosphorus and biogenic silica analyses have been completed on three primary cores. Beryllium-10 is used to help fingerprint sediment source, and samples have been prepared for five of the lakes. The majority of sediment analyses are still ahead.

Activity Status as of 31 December 2015:
Another coring trip was taken in September to acquire four more cores from Kansas Lake (Watonwan County). With two more cores from Big Elk Lake (Sherburne County) added to the project, our core total now stands at 43 surface cores, plus 9 deeper segments, for a total of 52 cores (not including reconnaissance cores discarded from rejected sites). We plan one more quick trip to collect two deeper (longer) cores from Richardson Lake (Meeker County), which will allow us to extend the record back to before pre-EuroAmerican settlement times for that lake. At that point, all fieldwork for the project will be completed.

Lab work has been the main focus of activity for the project during this reporting period. Initial core processing is nearly complete (90%). Loss-on-ignition analysis to determine organic, carbonate, and inorganic matter content is 75% complete, as are all dating methods (^{210}Pb, ^{137}Cs, and ^{14}C). Sediment dating is a critical step because further analyses depend on selection of samples from appropriate time intervals. So far, dating has proceeded well; all cores have well-behaved ^{210}Pb profiles in the sediment. Refining the dating with ^{137}Cs peaks has added some extra steps but also has improved the accuracy of the results. Samples have been selected and submitted to the University of Utah for ^{10}Be analysis, which will help determine the field versus non-field components of the sediment being deposited in the lakes.

The history of lake productivity (biological response to watershed inputs) is being explored with the analysis of total phosphorus, phosphorus fractions, and biogenic silica (diatom cell walls) in the lake sediment. Analyses of these critical components is about 33% complete, and has generated important new data regarding the mobility of phosphorus in the pore waters of lake sediment, and regarding the fidelity with which a phosphorus profile reflects external inputs from the watershed. The chemical behavior of phosphorus in lake sediment is a fundamental control in how lakes respond to watershed inputs of nutrients and become eutrophic over time, and how lakes may respond to efforts at remediation, either through improvements in watershed land-use practices or through whole-lake manipulation (alum treatments). Methods and results developed during the project should mesh well with other issues of interest to the State (eutrophication in boreal lakes, such as Lake of the Woods, and the increased frequency of harmful algal blooms).

Establishment of the CHARM lab (Activity 2, Outcome 2) is well underway. After several weeks of weighing options and specifications, an inverted microscope has been purchased, delivered, installed, and outfitted for analyses of algal samples. The microscope still needs to be fitted with a digital video camera to capture screen images. This instrument extends the capability of the state for taxonomic identification of algae, in particular the blue-green (cyanobacteria) group that can cause harmful algal blooms (HABs). In addition to identifying algae in modern water samples, it is further possible to isolate algal parts remaining in the lake sediment to obtain a record over time of algal species communities. This work has been pioneered by several Canadian scientists, who will visit our laboratory during the next year to consult with SCWRS scientists and develop a uniform methodology.

Activity Status as of 30 June 2016:
With the addition of sediment cores from Baby and Mountain lakes, our core total is now 46 surface (~1.5-m) cores plus 11 deeper core segments, for a total 57 cores. This will likely be our final total. Lab work to analyze these sediment cores has continued during this reporting period and is approaching completion for most tasks. All cores have been initially processed and subsampled, and analysis of basic sediment components (organic, inorganic, and carbonate matter) is 95% complete. Radioisotopic sediment dating to identify the age of the sediment samples is 85% complete. We are still awaiting result of ^{10}Be analysis, which will help partition field from non-field sources of the sediment. These analyses will frame the physical components of the sediment cores: basic sediment composition, sediment chronology, and the rate of accumulation of those components derived from soil erosion in the watershed. Our working hypothesis remains that lakes accumulate inorganic sediment at a rate that changes with land cover in the contributing watershed: low rates with native vegetation, high rates with row-crop agriculture, and reduced rates after implementation of agricultural best management practices.

Components more related to the biological response of the lakes to watershed inputs include sediment phosphorus content, biogenic silica content (a measure of algal productivity), pigment content, and diatom assemblages. Efforts are now focused on sediment phosphorus content; analyses are currently about 50% completed but should be done by the end of September. Sediment subsamples have been collected for pigment analysis and shipped to an external lab for analysis (University of Regina). Samples for diatom analysis have been selected and processed but are awaiting microscopic analysis.

Activity Status as of 31 December 2016:
Our work on Activity 2, Outcome 1, is nearly completed, as fieldwork is entirely done and our lab work is winding down to final analyses. Analyses of basic sediment components, phosphorus content (totals on all cores and extractable fractions on selected cores), and biogenic silica have been completed. We are, however, still awaiting (overdue) analytical results for samples sent to external universities for analyses. In particular, we are awaiting results of algal pigment analyses from the University of Regina and ^{10}Be analysis from Utah State University. We expect these results within two months. The algal pigment work will help identify the onset of blue-green algal blooms in the study lakes, and the ^{10}Be analysis will allow us to partition field from non-field (bank erosion) sediment sources. Diatom analysis of selected cores is also still pending.

Nonetheless, the principal results of this project depend critically on the radiometric dating of the sediment cores, which has now been completed through the combined use of ^{210}Pb, ^{137}Cs, and ^{14}C isotope analyses for all cores integrated into this study (Richardson, Solem, Dunns, Cedar, Big Elk, Barrett, Perkins, South Heron, Miller, and Fish). With these lake-sediment chronologies in hand we have begun the process of combining multiple cores from the same lake into a single whole-lake sedimentation rate. This process involves focus-correcting each core using the measured flux of ^{210}Pb at the core-site relative to the known atmospheric deposition rate in Minnesota and then uniformly interpolating sediment accumulation rates for each core on an annual scale from

1850 to present using a locally-weighted polynomial regression method (LOWESS). This has been completed for all of the above-mentioned lakes to produce whole-lake inorganic sedimentation rates. Because lakes efficiently capture most sediment delivered to them, lake-sediment accumulation is the best proxy available to estimate long-term watershed-scale soil erosion from the lake's catchment. An example of the data processing steps needed to interpolate sedimentation rates within a core, and to aggregate these rates across multiple cores from the same lake into a spatially averaged whole-lake rate, is shown in Fig. 6. A comparison of these whole-lake sediment accumulation rates – our proxy for watershed-scale erosion – for all ten lakes that have been completed is shown in Fig. 7.

In addition to the above lab work, this project has allowed significant expansion of our capabilities through the establishment of the CHARM lab (Activity 2, Outcome 2), i.e., the Center for Harmful Algal Research in Minnesota. Minnesota was lacking a dedicated research facility for studying many aspects of harmful algal blooms including the microscopical analysis of plankton collections and cyanobacterial microfossils preserved in sediments. Using LCCMR and additional funding, the SCWRS has leveraged expertise and analytical capacity and outfitted the new CHARM laboratory with a dedicated camera-ready inverted microscope, sample prep equipment, specialized literature, and we have increased the analytical capabilities of our lab to include immunoassay-based assessment of four cyanobacterial toxins that may be produced under bloom conditions.

The centerpiece of the new CHARM lab is an Olympus IX73 inverted microscope outfitted with brightfield and differential interference contrast optics capable of 100-600X magnification (Fig. 8). The scope is compatible with digital cameras and other objective systems in our laboratory. Inverted microscopes are primarily used to analyze well plate samples or samples prepared using settling chambers such as Ütermohl chambers. Analysis of cyanobacterial microfossils involves subsampling and preservation of sediment samples taken from dated sediment cores. Samples are appropriately diluted for analysis, placed in settling chambers, allowed to settle overnight, and analyzed by viewing and enumerating microfossils from multiple transects or fields. The technique can be further extended to analyze zooplankton and other biological remains in sediment cores. The microscope can also be used to analyze preserved plankton samples.

Additional supplies for sample preparation and analysis were also acquired for the lab. A set of custom settling chambers that are outfitted with No. 1 coverglass bases are necessary to minimize working distance for high magnification work. The excellent phycological library at the SCWRS was also supplemented with critical literature necessary to identify cyanobacteria. Additions to the lab include seminal works such as Komárek's 3-part series on the Cyanoprokaryota in the S*üsswassflora von Mitteleuropa* series and Hindák's *Atlas of the Cyanophytes*.

As hoped, the CHARM lab has been able to further expand its capabilities through additional funded projects. In particular, we have expanded our analytical capacity to include enzyme-linked immunosorbent assay (ELISA) of four cyanobacterial toxins—microcystin, anatoxin-a, saxitoxin, and cylindrospermopsin—through the acquisition of assay kits and a dedicated plate reader system (Abraxis, PA). The only toxin that had been previously measured in Minnesota lakes was microcystin; an increased capability to screen for additional cyanotoxins was a critical need for the state as cyanobacterial blooms have become a resource and health priority.

Final Report Summary:

Lake sediment collection and analysis

The foundational data collection efforts of this project were in the fieldwork to collect the lake-sediment cores and in the lab work to analyze the thousands of sediment samples extracted from these cores. During the first two years of the project we collected cores from three to six sites in each of the 12 primary lakes, for a total of 46 sites cored. Multiple cores per lake were necessary to allow quantitatively rigorous calculations of whole-basin mass accumulations of sediment and nutrients. Eleven of these required deeper core segments to be collected to reach pre-settlement times, for a total of 57 core segments collected for analysis. Most cores (44) were dated by ^{210}Pb method, which was checked for consistency with the 1963 ^{137}Cs peak. Likewise, most cores

(39) were analyzed for content of organic matter, carbonate matter, total phosphorus, and inorganic (eroded soil) matter. In total, over 4,000 separate analyses were performed on subsamples from these lake-sediment cores.

Trends in sediment and phosphorus accumulation

Based on the lake-sediment chronologies and contents as determined by the analyses above, we calculated the temporal trends in whole-basin accumulation rates for inorganic sediment (eroded soil) and total phosphorus for all cores in each of nine selected lakes in this study (Fig. 15; see also Fig. 7 for an alternate presentation in absolute, rather than relative, fluxes). These trends measure both the contribution of erosional material from the watershed as well as the transport and retention of the primary nutrient responsible for the eutrophication of inland waters (phosphorus). For each lake, we integrated data from the multiple cores into a single unified chronology by using locally weighted regression models to interpolate accumulation rates to an annual time-step in each core and then averaging the resulting rate for each year across all the cores from that lake (e.g., see Fig. 6). These data provide the best historical accounting of the initial response of lakes to land clearance, agricultural intensification, and the installation of best-management practices (BMPs) within their watersheds. Because the reference conditions of each lake will vary based on geographic variables (watershed size, topography, soils, vegetation, and climate), these data are presented as a magnitude of change relative to the "background" rate calculated as the average flux from 1850 to 1900. This "n-fold change" then represents how many times greater (or lesser) each flux is at any given time compared to pre-1900 conditions.

These data show a consistent trend, but large variation in the magnitude of sediment erosion to the lakes of this study. As expected, in most cases erosion began to rise shortly following land clearance (~1850-1900) and continued to rise throughout the 20th Century. Though some lakes showed a plateau or even decline in erosional rates (e.g., Barrett, Solem, Fish), all lakes continue to receive a sediment load 2-10 times their reference condition. On average, lakes in this study are currently receiving nearly 6-times more sediment than they were in 1850. Several of the lakes with the highest erosional rates show recent downturns (e.g., Richardson, Big Elk) which may point to the partial success of implemented BMPs in these watersheds, though it appears these reductions have been far outweighed by other changes to the watershed that have caused them to still be elevated 7-8 times pre-settlement rates. The deposition of total phosphorus in the lake sediments follows a similar trajectory across all the lakes in this study and demonstrates the direct link of erosion-fueled to nutrient pollution in lakes. Along with the sediments, these lakes had a 2 to 8-fold increase in sediment TP flux over the same time period. The change in these systems in the most recent 15 years (marked by the red dashed line) is more difficult to resolve due to the mobile nature of phosphorus within recent sediments, but we certainly cannot find any evidence for recent decreases in TP fluxes following the introduction of BMPs. On average, lakes in this study received up to 5-times more phosphorus to their sediments and this trend may have continued to increase in recent years.

Sediment fingerprinting and trends in sediment source

Sediment conservation BMPs are generally targeted at mitigating loss of soils from cultivated fields. However, erosion of near channel sources such as streambanks, ravines and bluffs can be significant contributors to the suspended sediment load in rivers. These near-channel, non-agricultural sources are referred to as non-field sources. Increases in non-field erosion and subsequent deposition in the lakes would contribute to observed increases of accumulation rates in the lake cores and could mask decreases in field erosion resulting from soil conservation BMPs.

To assess the importance of non-field contributions to current and historic sediment loading rates, we conducted sediment source apportionment (i.e., sediment fingerprinting) using ^{10}Be in eight of the watersheds. Beryllium-10 is a long-lived naturally occurring radionuclide that is deposited by precipitation on to soils. Cultivated fields with their extended exposure to precipitation are enriched in ^{10}Be as compared to streambanks and bluff which have minimal exposure to precipitation. By comparing the activity of ^{10}Be measured on sediments in the core to known values of ^{10}Be from field and non-fields sources, the relative contribution from each erosion source can be determined.

Sediment fingerprinting was done on seven to 12 intervals from the master core in eight lakes: Barrett, Big Elk, Cedar, Dunns, Fish, Kansas, Miller, and South Heron. In all eight lakes—and thus in their watersheds—erosion from upland sources (fields) was the dominant source of sediment. And surprisingly, the relative contribution from fields showed remarkably little change over time—although the magnitude of sediment eroded from uplands as increased 3 to 7 fold over time. In Barrett, Big Elk, Cedar, Dunns, Kansas, and Miller lakes, sediment eroded from uplands/fields contributed over 75% of the total sediment load both in the past and presently. In South Heron and Fish lakes, field-eroded sediments constituted 55 to 60% the total load. Fig. 16 shows the trend over the past 150 years of field and non-field loading from the Pomme de Terre river to Barrett Lake. The trend and relative dominance of field erosion observed in Barrett Lake is representative of the other watersheds.

In many tributaries to the Minnesota River, non-field sources have been shown to be the major contributor to riverine suspended sediment. Thus, given that lakes such as Barrett, Big Elk, Cedar and Miller collect sediment delivered from fairly large rivers, it is surprising that the proportion of sediment from non-field sources is not greater in these systems. However, all these lakes lie above the eroding knick zone of their watershed and are on rivers that have had comparatively small increases in flow. Results from these lakes demonstrate that in the upper portions of a watershed, particularly in those with smaller changes in hydrology, erosion from fields is the dominant source of sediment and that BMPs should be targeted at in-field processes. This is in contrast to studies on in rivers with actively eroding knick zones and greatly altered hydrology, where BMPs need to be targeted at preventing erosion of near-channel sources such as streambanks. The minimal inputs from non-field sources in our study lakes also largely eliminates the hypothesis that increased inputs from non-field erosion has masked or negated any positive effects of BMPs in reducing field erosion.

CHARM lab: Center for Harmful Algal Research in Minnesota

As noted in earlier workplan-update reports, this project has allowed significant expansion the capabilities of the St. Croix Watershed Research Station through the establishment of the CHARM lab (Activity 2, Outcome 2), i.e., the Center for Harmful Algal Research in Minnesota. Minnesota was lacking a dedicated research facility for studying many aspects of harmful algal blooms including the microscopical analysis of plankton collections and cyanobacterial microfossils preserved in sediments. Using LCCMR and additional funding, the SCWRS has leveraged expertise and analytical capacity and outfitted the new CHARM laboratory with a dedicated camera-ready inverted microscope, sample prep equipment, specialized literature.

The centerpiece of the new CHARM lab is an Olympus IX73 inverted microscope outfitted with brightfield and differential interference contrast optics capable of 100-600X magnification (Fig. 8). The scope is compatible with digital cameras and other objective systems in our laboratory. Inverted microscopes are primarily used to analyze well plate samples or samples prepared using settling chambers such as Ütermohl chambers. Analysis of cyanobacterial microfossils involves subsampling and preservation of sediment samples taken from dated sediment cores. Samples are appropriately diluted for analysis, placed in settling chambers, allowed to settle overnight, and analyzed by viewing and enumerating microfossils from multiple transects or fields. The technique can be further extended to analyze zooplankton and other biological remains in sediment cores. The microscope can also be used to analyze preserved plankton samples.

As hoped, the CHARM lab has been able to further expand its capabilities through additional funded projects. In particular, we have expanded our analytical capacity to include enzyme-linked immunosorbent assay (ELISA) of four cyanobacterial toxins—microcystin, anatoxin-a, saxitoxin, and cylindrospermopsin—through the acquisition of assay kits and a dedicated plate reader system (Abraxis, PA). The only toxin that had been previously measured in Minnesota lakes was microcystin; an increased capability to screen for additional cyanotoxins was a critical need for the state as cyanobacterial blooms have become a resource and health priority.

ACTIVITY 3: Quantify BMP effectiveness by linking land to water with statistical analyses and modeling
Description: The first step in statistical data analysis will be to search for trends in the water-quality records as inferred from lake-sediment analysis. In particular, we seek to test the working hypothesis that the peak in water-quality degradation occurred in the mid- to late-20th century as a consequence of poor farming practices, and that water quality has improved as farming practices have become more conservation-minded. What pattern is evident in the lake-sediment core records of water quality? Differences among time periods will be assessed by common non-parametric tests (Mann-Whitney or Kruskal-Wallace tests). Or, where appropriate, trends tests will be applied to assess change over time and rate of change. The second data analysis step will seek correlations between changes in water quality and changes in land use and BMP implementation. Do changes in water quality occur at the same time as those on the land, or are there lags in the response? Are there compensating factors that mutually mask the effect of the other? Distinguishing among the multiple possible factors will require careful analysis of (a) chemical or radioisotopic signatures that bear fingerprints of their sources, and (b) timing and magnitude of changes.

Because correlation is not causation, we will model watershed processes in order to assess whether purported correlations are mechanistically realistic. In this project, we plan to constrain the model to not only present-day data, but to past data as well as reconstructed from the sediment cores. We will use the Soil and Water Assessment Tool (SWAT), a watershed modeling program developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA). Model construction requires inputs of hydrography, topography, soils, land cover, and agricultural management practices, all of which will be compiled during Activity 1 above. For each study watershed, a SWAT model will be calibrated to the recent land-use and climate conditions, probably a 2000-2010 average condition. In particular, the model will be constrained to match the sediment and phosphorus loads inferred from the sediment core data for this recent time period. Then, the model will be tested by its ability to simulate loads of sediment and phosphorus for selected periods in the past. Model parameters will be adjusted to past conditions first by altering land cover, then management practices, to allow assessment of model sensitivity to these factors independently. Finally, the model will be run with a land cover of native vegetation to match pre-euroamerican loads inferred from the sediment core, which will provide a bracketing end member of model results that should help constrain certain model parameters to account for inherent landscape features (i.e., topographic complexities) whose effects might otherwise be confounded by human impacts. These models, constrained to past conditions by the sediment-core data, will help explain relative differences in apparent BMP effectiveness driven by differences in soils, topography, and climate among the study watersheds.

Summary Budget Information for Activity 3:	**ENRTF Budget:**	**$ 293,771**
	Amount Spent:	**$ 293,771**
	Balance:	**$ 0**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. Correlate sediment records to land-use and BMP histories	Mar 2017	$ 73,000
2. Construct computer watershed models	Mar 2017	$ 220,771

Activity Status as of 31 December 2014:
No activity during this reporting period.

Activity Status as of 30 June 2015:
No activity during this reporting period.

Activity Status as of 31 December 2015:
Work on this activity targeted creating a uniform format for our lake-sediment stratigraphic data. This is the first step in allowing the sediment data to be statistically analyzed in relation to watershed histories of land use and BMP implementation.

Activity Status as of 30 June 2016:
Watershed modeling is a key tool to link landscape activity to water-quality impacts on lakes, with significant progress on this outcome during this reporting period. In particular, a model was constructed for the Pomme de Terre River watershed, which comprises the contributing area to Barrett and Perkins lakes, both of which were cored for this project (Fig. 5). Barrett Lake, one of our primary lakes, lies in the middle of the watershed and is most directly influenced by a relatively small area (60 km^2). However, to include total inputs to the lake from the entire up-river watershed and to calibrate the model to flow measurements at the river mouth, the entire Pomme de Terre watershed was modeled (2,164 km^2). The watershed was subdivided into 395 subbasins. Besides Barrett and Perkins lakes, the 31 largest lakes in the watershed were also included in the model because of their critical effects on flow and water quality. The many other smaller lakes and wetlands were modeled with impoundment tools available in SWAT. Land use and current cropping practices were obtained by overlaying the last five years of the USDA's Cropping Data Layer (CDL) digital land-use, from which representative crop rotations were developed. Corn and soybeans are by far the most common crops, comprising 90% of the cropped area. The remaining 10% is in wheat, alfalfa, and sugar beets (Fig. 5). Further intersection of these land use categories with land slope and SSURGO soils types resulted in 3,207 unique combinations called "hydrologic response units" or HRUs, which are aggregated units within each subbasin that share a uniform rainfall-runoff response. Each HRU in the model is commonly larger than an individual field on the landscape but can be thought of as a "super-field" composed of identical field types (same crop, soil, and slope) from within the same subbasin. This aggregation of many smaller units into a lumped unit makes the model calculations tractable on a desktop computer. Watershed modeling provides a measure of landscape scale erosion that is independent of that derived from the lake-sediment studies. There is error in both methods, but by reconciling the results of the two methods, we can constrain the errors, triangulate a more accurate answer, and learn more about mechanism of transport.

Activity Status as of 31 December 2016:
The completion of whole-basin averages from our sediment core data allows us to begin direct comparison to coincident land use changes in the respective watersheds. Our estimated whole-basin inorganic sediment accumulation rates (watershed erosion) for each lake is compared to acres of row-crop, acres of small grains, conservation tillage practices, and BMPs that replace farmed land with perennial vegetation. This combined comparison of watershed practices and sediment erosion to lakes has been completed for the ten study lakes for which whole-basin sedimentation rates have been calculated (See Activity 2 status update). An example of the correlative analysis these data provide is shown in Fig. 9. This analysis allows us to compare the acres of cropland in the watershed (gleaned from countywide agricultural survey statistics scaled to the lake watersheds) annually from 1920 to present versus the whole-basin watershed erosion rates over the same time period. We are also able to evaluate the relative effects of conservation tillage (from 1989 to 2007) and the percentage of farmland in the watershed converted to perennial vegetation BMPs (data available for 1993 and 2004). The correlation of land-use history with the sediment-core record is a fundamental step in inferring human impacts on soil erosion and water quality. The next step is to seek the mechanisms that link land to water, and for that we use watershed models.

Watershed models have been constructed for two of our lake systems (Barrett and Solem), with more models planned for the watersheds of our remaining primary lakes. The same land-history data used for the correlative data analysis above are also used as boundary conditions to configure land cover and management practices in our watershed models for selected time intervals in the past. Our selected time periods for our pilot analysis includes the pre-EuroAmerican settlement period (<1860), widespread agricultural expansion prior to many conservation programs (1961-85), after conservation practices began to be adopted (1986-2005), and the modern period of increased corn and soybean acreage in the face of increased adoption of conservation tillage practices (2006-15). As noted in the previous update, our pilot model is for our Barrett Lake site in the Pomme de Terre watershed in western Minnesota (Fig. 5), for which we have constructed a model using the Soil and Water Assessment Tool (SWAT). This model has been calibrated to data collected by the Minnesota Pollution Control Agency at Appleton, MN, near the confluence of the Pomme de Terre River with the Minnesota River. In addition, model parameters were adjusted to match the modern sediment accumulation rates in both Barrett Lake and Perkins Lake. Figure 10 shows Barrett Lake sediment accumulation rates calculated from both the sediment core record (blue) and the SWAT model (red). The bars represent average rates over our four selected time intervals. As can be seen, the model matches the lake-sediment record closely for the modern period and the presettlement period, but is somewhat less than the rates during the 1961-85 and 1986-2005 periods. These results show that the range of response of the watershed model, from presettlement times to today, can be adjusted to match that of the lake sediment data. This congruency supports the contention that these independent measures (lake sediment accumulation and watershed modeling) are each providing reasonable estimates of long-term, landscape-scale erosion. Further, the trend of erosion rates over time is the same in both the watershed model and lake-sediment record. However, the difference between the estimates for the two middle periods (1961-1985 and 1986-2005) makes evident that there are uncertainties in the results that would be beneficial to resolve. While there are errors in both methods, we suspect that the model is missing some of the details of erosion in the watershed that can cause it to over- or under-estimate sediment loads under different conditions. Our next step is to examine model output more closely to see if we can find instabilities in the model that may explain the jump in erosion during the early 2000s.

A second watershed model has been constructed for the tiny Solem Lake watershed (Fig. 11), using a GIS landscape analysis tool called PTMapp. Because this watershed has no perennial streams, nor does the lake have an outlet, conventional monitoring data (e.g., stream-flow and water-quality samples) does not exist, and the SWAT model did not seem appropriate. In contrast, PTMapp utilizes detailed topographic data from LiDAR that allows greater spatial detail for small watersheds such as that of Solem Lake. However, PTMapp gives only average annual values of runoff and erosion under selected land-use conditions, in contrast to the daily estimates generated by SWAT using actual rainfall records. Hence PTMapp can only compare the effect of differences in land use, and not changes in rainfall, over time (at least, not as PTMapp is conventionally used).

PTMapp erosion relies on the RUSLE model (Revised Universal Soil Loss Equation) for its gross erosion rates but also factors in the effect of flow distance to downstream waterbodies. Hence the amount the eroded sediment predicted to reach Solem Lake is a function of that predicted by RUSLE less the amount of sediment predicted to deposit prior to reaching the lake. The PTMapp model was configured for two conditions: (1) Corn and/or Soybean on both fields; (2) CRP grassland on both fields. Beyond these cover types, all other variables were held constant. Model and observed sediment core results are presented in Fig. 12. PTMapp results match the core results very well from 1850 to 1900 (assumed pre-row crop agriculture) and around 1960 to 1986 (assumed corn-soybean agriculture). However, modeled vs. core results do not match well for the conversion of corn-soybean to CRP grassland from 1986 to approximately around 2010; during this period, the PTMapp model substantially under-estimates sediment delivery to the lake relative to the core results. The PTMapp results will be further refined to take into account varying climate over the study period in an effort to better match the variability in the core results.

Final Report Summary:

The dated sediment cores show substantial variability in their sediment accumulation rates (as a measure of watershed-scale erosion), but they are all consistent in showing that current rates are many times the natural rates prior to settlement. The next step in the data analysis was to correlate known land-use changes in each basin to the erosion story recorded in the lake sediments. Fig. 17 shows this correlative analysis for six of our study lakes and watersheds, where in general the rise in sediment accumulation following settlement matches well with the increase in row crops (yellow line), here being corn, soybeans, and sometimes sugar beets. The rise in row crops is the mirror image of the decline in hay and small grains (green line). The match between sediment and row crops is quite good for Miller, Richardson, and South Heron lakes (Fig. 17 a-c), whereas the timing of the sediment inputs is somewhat different from the rise in row crops, as for Big Elk and Barrett lakes. These are riverine lakes that have filled in substantially since the time of settlement, and consequently their sediment trapping efficiencies have probably declined over time. In all cases the area of BMPs (here showing just conservation tillage and CRP) are much smaller than the total cropland acreage. Nonetheless, it is possible that some of the leveling off of sediment accumulation may be related to implementation of these BMPs, thereby countering some of the effect of increased areas of cropland.

Another view of the same data (Fig. 18) shows that the increase in BMPs (green bars, as a percent of the lake's contributing basin) was commonly exceeded by the increase in row crops (gold bars). Hence, despite BMP implementation, the net result was still an increase in soil erosion as measured by lake sediment accumulation (red bars).

The variability among lakes in their responses to changes in land use (cropping practices and BMPs) is not surprising, given the wide variety of landscapes, soils, topography, and climate that occurs across the agricultural-dominated landscape in the southern half of the state. To help account for these extra factors, watershed models were fit to a selected subset of the lakes. These models simulate not only the in-field processes that lead to soil erosion and nutrient loss, but also all of the transport processes that act to deliver these nonpoint-source pollutants to our rivers and lakes. Our goal in the modeling was to provide an independent estimate of past soil erosion and sediment delivery to our study lakes, for comparison with the erosion history documented in the lake-sediment record. We chose four time periods for this comparison. The period before 1860 represents natural, presettlement conditions, the period 1961-85 represents the widespread expansion of mechanized agriculture, the period 1986-2005 represents a period of BMP encouragement, and the period 2006-15 represents the recent expansion and dominance of corn-soybean row crops.

We chose two modeling frameworks, based on scale and data availability for our study lakes. For lakes in large watersheds with several decades of flow records available for calibration, we used the Soil and Water Assessment Tool (SWAT), a program developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA). SWAT is the right tool for estimating delivery of sediment and nutrients to lakes when these pollutants come predominantly from a large contributing area rather than from local sources. For lakes in small watersheds without flow data available, we used PTMapp, a modeling program that uses much more detailed spatial data as input, including newly available LiDAR topographic data. In contrast to SWAT, which generates daily sediment loads in response to actual rainfall records, PTMapp gives only average annual values of runoff and erosion under selected land-use conditions. Nonetheless, the annual temporal resolution of PTMapp is more than adequate for comparison to the sediment record, whose temporal resolution is limited to multi-year averages, typically decadal.

For SWAT modeling, we selected the watersheds of two principal lakes, Barrett and Big Elk lakes (Fig. 1). Both lakes are on substantial rivers with long flow records, allowing good model calibration and also providing test cases to compare the loading of field versus non-field sediment to the lakes. Barrett Lake is on the main stem of the Pomme de Terre River (Fig. 5). We added Perkins Lake in the same watershed as an auxiliary site to increase our knowledge of sediment transport within nested hydrologic systems. The Barrett Lake sediment core shows a steady increase in sediment accumulation from the time of settlement to about 1960, followed by a leveling off (Fig. 19a, blue line). Simulated loads from the SWAT model did a good job matching both presettlement and current rates but underestimated 1960-2005 rates (Fig. 19b, red lines). In Perkins Lake, the model did a good job matching current and 1960-2005 rates but overestimated presettlement rates (Fig. 19b, red lines). Perkins is just downstream from another lake, and sediment delivery to Perkins is controlled strongly by the sediment trapping efficiency of this upstream lake, thereby making the sediment record in Perkins complicated. Big Elk Lake is on the Elk River, and its sediment record shows a rapid rise starting just prior to 1900, but then declining for the next 80 years (Fig. 19c, blue line). This decline may be due to the lake becoming shallow enough from sediment infilling that its sediment trapping efficiency declined over time, overwhelmed only the recent pulse of sediment added by increased row crop acreage. The SWAT model (Fig. 19c, red lines) tried to take into account the effect of the lake getting shallower. It did a good job matching recent and presettlement sediment accumulation rates but overestimated the 1960-85 period.

For PTMapp modeling, we selected the watersheds of two of our smaller principal lakes, Solem and Richardson lakes (Fig. 1). Compared to our other lakes, Solem Lake has a tiny watershed with two main fields (Fig. 11), which should allow a direct relation between soil erosion and lake-sediment accumulation, with minimal complications caused by transport factors. PTMapp erosion relies on the RUSLE model (Revised Universal Soil Loss Equation) for its gross erosion rates but also factors in the effect of flow distance to downstream waterbodies. Hence the amount the eroded sediment predicted to reach Solem Lake is a function of that predicted by RUSLE less the amount of sediment predicted to deposit prior to reaching the lake. The PTMapp model was configured for two conditions: (1) Corn and/or Soybean on both fields; (2) CRP grassland on both fields. Beyond these cover types, all other variables were held constant. Model and observed sediment core results are presented in Fig. 12. PTMapp results match the core results very well from 1850 to 1900 (assumed pre-row crop agriculture) and around 1960 to 1986 (assumed corn-soybean agriculture). However, modeled vs. core results do not match well for the conversion of corn-soybean to CRP grassland from 1986 to approximately around 2010; during this period, the PTMapp model substantially under-estimates sediment delivery to the lake relative to the core results. The model calculated erosion under CRP to be essentially the same as under native prairie, i.e., presettlement conditions, whereas in the real world there may be a lag in response that is not simulated, or perhaps there is an additional contribution to the sediment load unaccounted for in the model. These results are consistent with the hypothesis that deposition of wind-blown sediment could be adding to the current base level of sedimentation in nearly all of our lakes.

Overall, the SWAT and PTMapp modeling confirmed that the general magnitude of sediment delivery to lakes, as measured by lake sediment accumulation, can be quantitatively and mechanistically related to land-use activities that cause soil erosion. All of our lake-sediment data and all of our modeling results indicated substantial increases in soil erosion and lake-sediment accumulation at the same time and total magnitude. While it may seem obvious that soil erosion is the cause of siltation in our rivers and lakes, it is quite another thing to demonstrate a quantitative linkage that is consistent with independently derived empirical data and modeling results. It is the hallmark of good science to use independent methods to triangulate in upon a solution that is more robust than would be possible with either method alone. On the other hand, the mis-match in some of the details between watershed models and lake-sediment data over the last 60 years demonstrates that models still lack some of the idiosyncratic features in watersheds that can complicate sediment generation, transport, and delivery to lakes.

ACTIVITY 4: Transfer knowledge to resource managers

Description: To inform resource managers, we will host a half-day workshop in the Twin Cities to present project results to state, local, and federal agency personnel. For broader dissemination, the workshop content will be tailored to each study watershed and presented to local officials at out-state venues. In addition, we will produce a series of fact sheets (2-4 p. each), for each of the detailed-study watersheds for use by local resource managers. These fact sheets will be targeted for the educated lay reader, to assist local managers in making and justifying BMP implementation decisions. A final project report will document all findings for reference by state personnel, and publications in peer-reviewed journals will inform the wider academic research community.

Summary Budget Information for Activity 4: **ENRTF Budget: $ 47,000**
Amount Spent: $ 47,000
Balance: $ 0

Activity Completion Date:

Outcome	Completion Date	Budget
1. Hold workshops & write fact sheets: Twin Cities & study watersheds	Jun 2017	$ 47,000

Activity Status as of 31 December 2014:
No activity during this reporting period.

Activity Status as of 30 June 2015:
No activity during this reporting period.

Activity Status as of 31 December 2015:
No activity during this reporting period.

Activity Status as of 30 June 2016:
No activity during this reporting period.

Activity Status as of 31 December 2016:
No activity during this reporting period.

Final Report Summary:
A number of workshops and presentations based on this project have been given to groups in out-state Minnesota (see below) and centrally in the Twin Cities. The main themes of information given cover these topics:

- The rates of sediment and nutrient loading to our rivers and lakes have increased greatly since the time of settlement and correlate most strongly with acreage of row crops.
- Implementation of BMPs can be locally good and may have kept sediment and nutrient loads from getting much worse in some places, but they have not resulted in widespread improvement of water quality across the agricultural region of Minnesota. Increases in BMP implementation have been counter-balanced or simply overwhelmed by increases in row-crop acreage, as corn and soybeans have replaced forage crops and small grains. Figure 20 summarizes these first two points, using Barrett Lake as an example.
- An alternative to the conventional BMPs employed today is to keep living green cover on the fields as long as possible each year. However, farmers are unlikely to implement living cover on fields unless it is profitable to them. Hence, the challenge is to create new markets for crop rotations that achieve this goal.

Two presentations have been given to the Clean Water Council on the effectiveness of BMPs and the need for landscape-scale change. We have also presented to, and participated in, the “Moving the Needle” task force to summarize and make recommendations as a follow-up to Governor Dayton’s Water Summit. Further, a special session will be held at this year’s Minnesota Waters conference on “The Need for and Potential of Creating Markets for BMPs.” Invited presenters include Friends of the Mississippi River, Minnesota Environmental Partnership, Land Stewardship Project, Forever Green (Univ. of Minn.), The Nature Conservancy, and the Great Plains Institute.

Presentations to other groups include the following:

- Working Lands Group, organized by BWSR
- Greater Blue Earth River Basin Alliance
- Chippewa Watershed “10% Project”
- Isaac Walton League (joint meeting for southern Minnesota chapters)

- Lake Pepin Legacy Alliance
- Friends of the Mississippi River
- Upper Mississippi River Conservation Alliance (in partnership with the U.S. Fish and Wildlife Service)
- Friends of the Star Prairie Land Preservation Trust
- Great Lakes Protection Commission (national meeting)

V. DISSEMINATION:

Description: Activity 4 of this project (see above) focuses on knowledge transfer to watershed resource managers through a series of half-day workshops. These will include the following:

- One half-day workshop in the Twin Cities to present results to state and federal resource managers and interested university scholars
- One half-day workshop for each study watershed to present results to local resource managers at out-state venues.

In addition, we will produce a series of fact sheets (2-4 p. each), for each of the detailed-study watersheds for use by local resource managers. These fact sheets will be targeted for the educated lay reader, to assist local managers in making and justifying BMP implementation decisions. A final project report will document all findings for reference by state personnel, and publications in peer-reviewed journals will inform the wider academic research community.

Status as of 31 December 2014:
Paper presentation at international conference:
Dietz, R.D., Engstrom, D.R., Almendinger, J.E., and Schottler, S.P. 2014. Sediment accumulation rates in Minnesota (USA) as understood through the lens of land-use history. Oral presentation at the 2014 Geological Society of America meeting in Vancouver, BC, 19-22 October 2014.

Status as of 30 June 2015:
Dan Olson, Minnesota Public Radio Sounds and Voices. Audio fieldtrip accompanying coring trip to Solem Lake, Douglas County, near Alexandria, on 27 May 2015. Aired on 11 June 2015.
See http://www.mprnews.org/story/2015/06/11/msv-sediment-and-farming.

Paper presentation at international conference:
Almendinger, J.E., and Ulrich, J. 2015. Spatial scaling of phosphorus export coefficients and load reductions due to agricultural best management practices. 2015 International SWAT Conference, Pula, Italy, 24-26 June 2015.

Status as of 31 December 2015:
No activity during this reporting period.

Status as of 30 June 2016:
No activity during this reporting period.

Status as of 31 December 2016:
No activity during this reporting period.

Final Report Summary:
In addition to the final report summary given above for Activity 4 (Transfer knowledge to resource managers), we are preparing fact sheets summarizing the major components of this project. The fact sheets will be 2-4 pages long and targeted towards both watershed managers and an educated lay audience.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Explanation
Personnel:	$ 617,771	1 sediment geochemist at 8% FTE for 3 years; 1 sediment radioisotope analyst/geochemist at 75% FTE for 3 years; 1 diatom analyst at 75% FTE for 3 years; 1 hydrologist/watershed modeler at 65% FTE for 3 years
Professional/Technical/Service Contracts	$ 56,439	Analyses by external labs (Be-10, C-14, pigments, phosphorus fractions)
Equipment/Tools/Supplies:	$ 43,000	$5K field supplies (tubing, tape, vials, misc.); $31K lab supplies (reagents, glassware; replacement parts);-$7K data analysis supplies (data acquisition; software)
Capital Expenditures over $5,000:	$ 30,000	Inverted microscope
Travel Expenses in MN:	$ 2,590	$2,300 for coring fieldwork; $290 for results dissemination workshops.
Other -- Analytical Services:	$ 150,200	Lab analysis of sediment cores: sediment components (organic, carbonate, inorganic fractions); radiometric dating and sediment fingerprinting (Lead-210, Cesium-137); biogenic silica (algal productivity); sediment phosphorus content; diatom community; blue-green algal fossils.
TOTAL ENRTF BUDGET:	**$ 900,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: An inverted microscope (with the objective below the stage) is required for identifying and counting algal parts isolated from water or sediment samples. With proper maintenance, this microscope has an indefinite lifetime and is expected to be in service for many years.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 7 FTEs

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
Science Museum of Minnesota	$ 387,000	$ 387,000 as of 30 Jun 2017	Unrecovered support services (lab & equipment maintenance, infrastructure, project administration), 43% of direct costs
TOTAL OTHER FUNDS:	**$ 387,000**	**$ 387,000**	

VII. PROJECT STRATEGY:

A. Project Partners: None.

B. Project Impact and Long-term Strategy: Undoubtedly, Minnesota waters have been impacted by human activities since the time of euroamerican settlement, which began in earnest in the mid-19th century. No data exist to docment the pristine, natural state of water quality prior to this settlement. After more than a century of agricultural and urban growth, regulations to protect and improve water quality were finally established, principally by the 1972 Clean Water Act. Water-quality monitoring began to be more common but the degree of pollution was difficult to assess because of the lack of baseline data. After spending billions of dollars nationally to clean up point sources of polluton with good success, we are now spending billions of dollars on best management practices (BMPs) to address nonpoint-source pollution. Unfortunately, the effectiveness of BMPs is difficult to assess at the watershed scale because the potential benefits of BMPs become mixed with and overwhelmed by continuing changes in land use, especially agricultural practices driven by policy decisions. Many Minnesota water bodies remain impaired. Fortunately, the Minnesota Clean Water, Land, and Legacy Amendment has provided critical funds to reinvigorate our efforts, both for water-quality monitoring and for BMP implementation. Still, without long-term data sets to documenting baseline water quality, we cannot easily quantify the net effects of BMPs in the context of other watershed influences. In summary, because of the lack of long-term water-quality data, we don't know where we started from, how far we've been blown off course, and whether we're making progress against stiff headwinds.

The importace of this project lies in filling this data gap: we will reconstruct long-term records reflective of water quality from clues preserved in lake sediments. Each year, a lake lays down a layer of sediment, the composition of which can be used to infer watershed-scale loads of sediment and nutrients. As noted earlier, this approach has been used with success for very large basins: Lake Pepin sediments document the nonpoint-source pollution history of the upper Mississippi River basin, as do Lake St. Croix sediments for its basin. We will build on these successes by selecting another five to ten lake basins within Minnesota for a similarly detailed assessment of whole watershed loads of sediment and nutrients. The chronology of these loads will be compared with the histories of land use and BMP implementation in each basin to help tease apart the multiple possible pollutant sources. Finally, watershed models will be fit to these basins as constrained by the long-term data extracted from the sediment-core records, thereby both testing and improving the models while providing another method of distinguishing among possible pollution sources. The benefits include development of critical long-term data sets, a test of BMP effectiveness at the scale at which our waters are deemed impaired, and improvement of modeling tools to make results more realistic and predictive. The long-term data sets will greatly enhance the value of existing watershed monitoring in the state by providing temporal context, without which the current records are unanchored relative to natural, pre-industrial conditions.

C. Spending History:

Part 1: Funding Source	**M.L. 1995 or FY96**	**M.L. 1999 or FY00**	**M.L. 2002 or FY03**	**M.L. 2007 or FY08**	**M.L. 2008 or FY09**
Met Council (for mass balance of sediment and phosphorus to Lake Pepin)	$ 150,000				
ENRTF (ML 1999, Chap. 2331, Sec. 16, Subd. 6b; for sediment fingerprinting of sediment sources in agricultural watersheds)		$ 350,000			
Met Council & MPCA (for mass balance of sediment and phosphorus to Lake St. Croix)			$ 250,000		
ENRTF (ML 2007, Chap. 30, HF293, Sec. 2, Subd. 5d; for demonstrating benefits of conservation grasslands)				$ 374,00	
MPCA (for construction and application of a computer model of the Sunrise River watershed to address nonpoint-source pollution loads)					$ 137,000
Part 2: Funding Source	**M.L. 2008 or FY09**	**M.L. 2009 or FY10**	**M.L. 2011 or FY12**	**M.L. 2012 or FY13**	**Total, Parts 1 & 2**
Nat'l Park Service (for construction of a computer model of the St. Croix River watershed to address nonpoint-source pollution loads)	$ 200,000				
ENRTF (ML 2009, Chap. 143, Sec. 2, Subd. 5d; for effect of tile drainage on river flow and erosion)		$ 300,000			
MPCA (matching 319 funds for above project)		$ 300,000			
MPCA (for Lake of the Woods phosphorus loading and sediment interaction problems)			$ 150,000, +$ 150,000 for FY14		
MPCA (for continued sediment fingerprinting work)				$ 250,000	
Plus numerous small projects documenting watershed-scale, long-term histories of atmospheric and other nonpoint-source pollution loads					
TOTAL					$ 2,611,000

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. VISUAL ELEMENT or MAP(S): See attached figure.

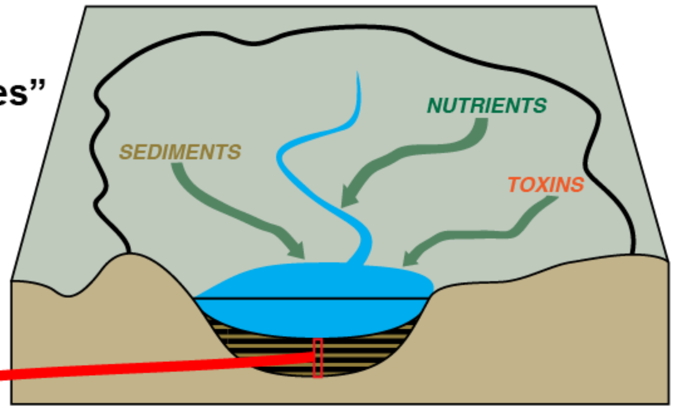
X. ACQUISITION/RESTORATION REQUIREMENTS WORKSHEET: N/A

XI. RESEARCH ADDENDUM: See attached Research Addendum.

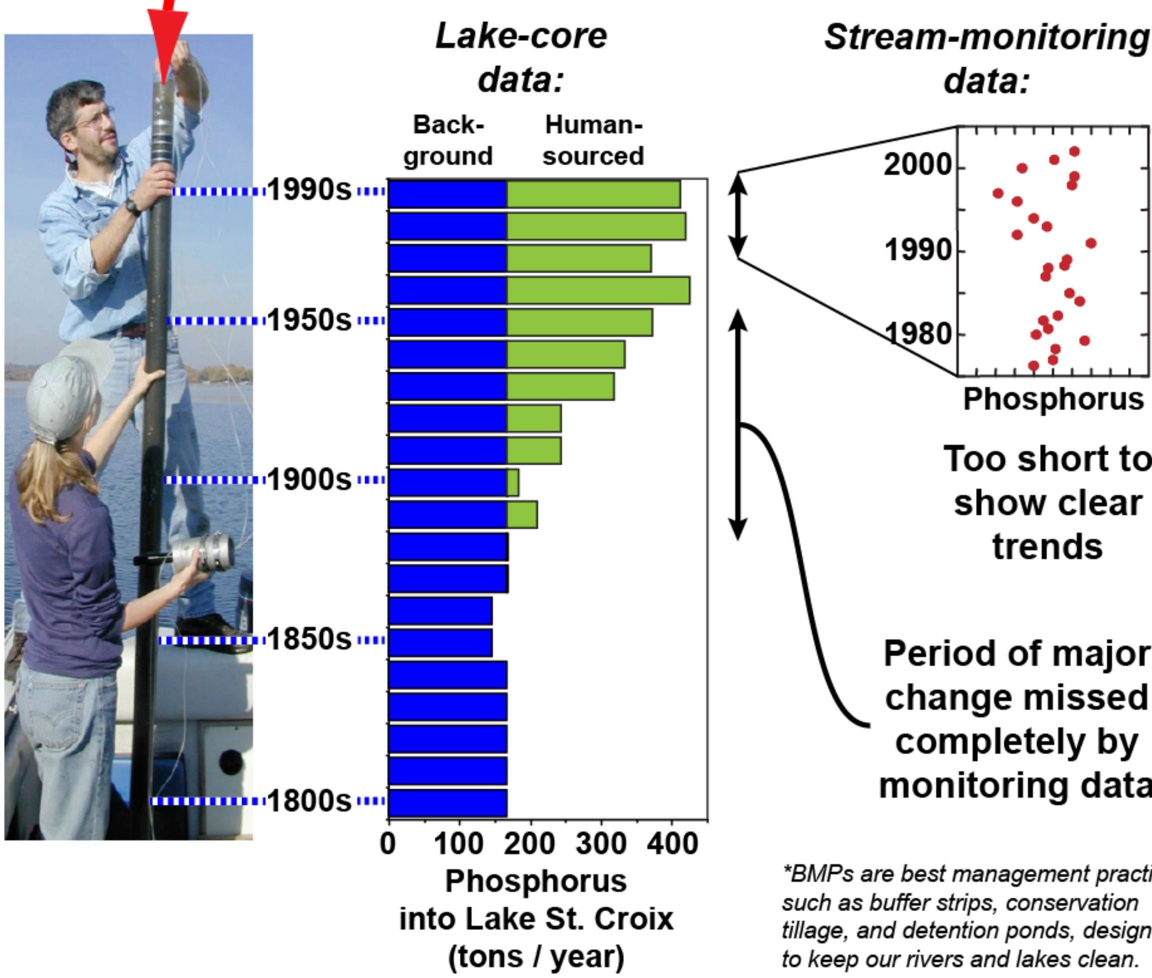
XII. REPORTING REQUIREMENTS:
Periodic work plan status update reports will be submitted no later than the end of the months of January 2015, July 2015, January 2016, July 2016, and January 2017. A final report and associated products will be submitted between June 30 and August 15, 2017.

- ***Have BMPs* been effective?*** *Virtually no data exist at the watershed scale to answer this question.*
- ***Lake sediments offer a way of going back farther in time to see a more complete picture.***

Lakes collect long-term, watershed-scale "samples" *before and after* BMP implementation.



Each slice of a lake-sediment core is a slice of watershed history.



**BMPs are best management practices, such as buffer strips, conservation tillage, and detention ponds, designed to keep our rivers and lakes clean.*

Figures for Work Plan Updates:

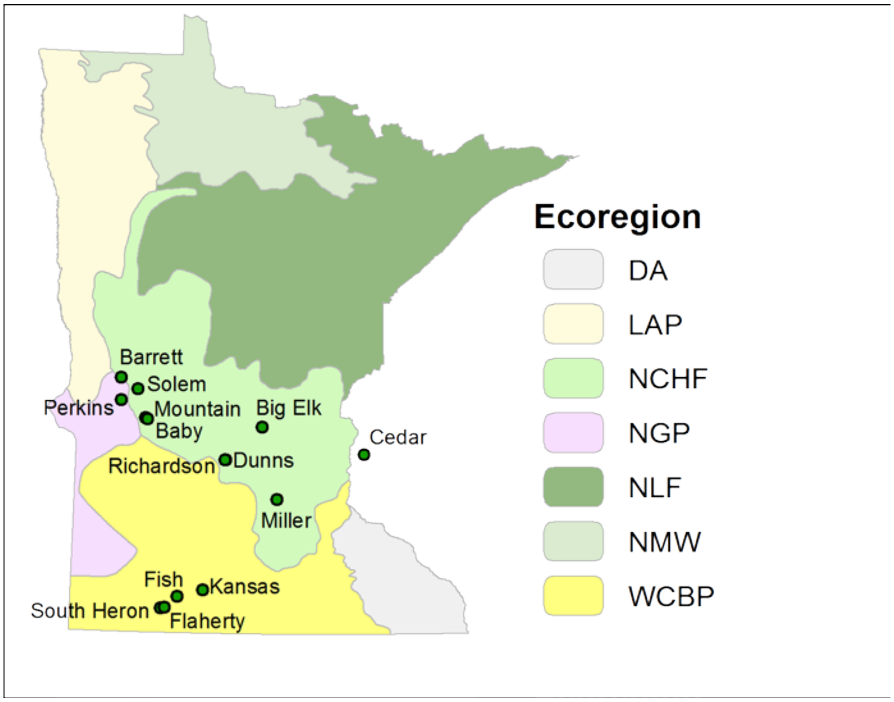


Figure 1. Lakes where sediment cores for this project were collected as of 31 Dec 2015.
NOTES: DA = Driftless Area; LAP = Lake Agassiz Plain; NCHF = North Central Hardwood Forest; NGP = Northern Great Plains; NLF = Northern Lakes and Forest; NMW = Northern Minnesota Wetlands; WCBP = Western Corn Belt Plains.

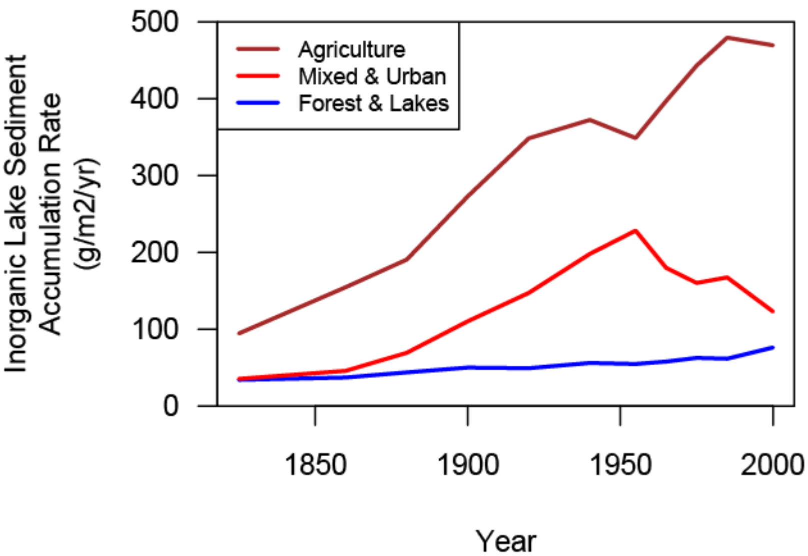


Figure 2. Accumulation rate of inorganic sediment in lakes as a proxy for watershed-scale soil erosion since the time of Euro-American settlement, stratified by dominant land cover.
NOTES: Data from 116 lakes in archived core data base maintained by the St. Croix Watershed Research Station. Each value represents the median for each category during each decadal time slice.

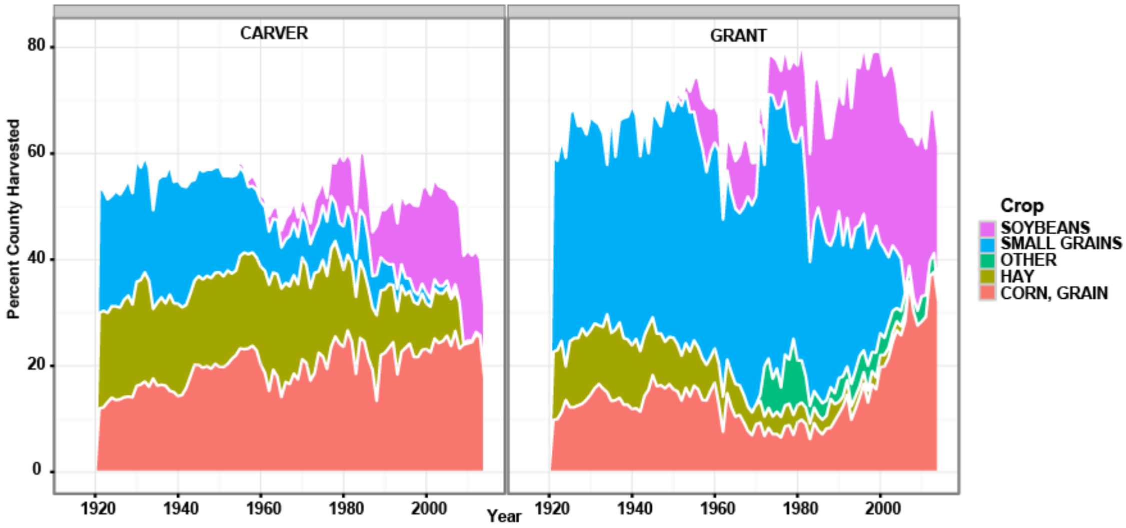


Figure 3. Cropping history of Carver and Grant counties, 1920-2010.
NOTES: Source: U.S. Department of Agriculture National Agricultural Statistics Service (USDA NASS): http://www.nass.usda.gov/Data_and_Statistics, accessed June 2015.

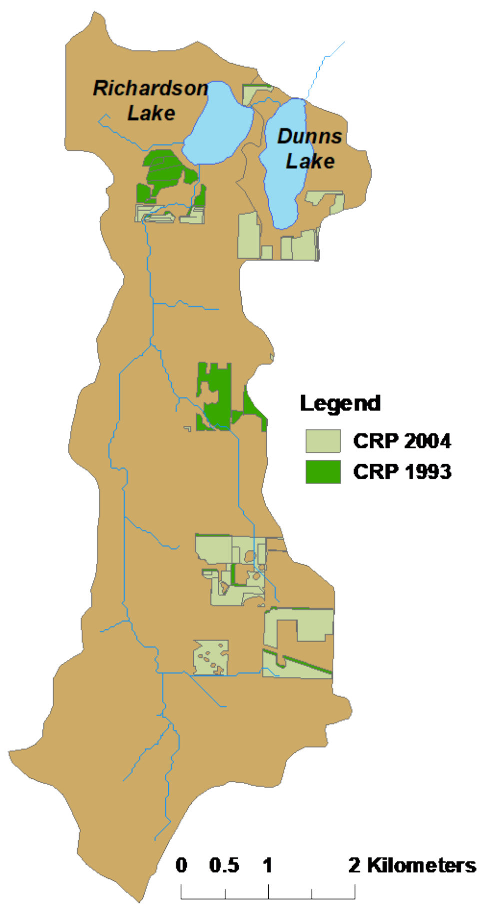


Figure 4. Watershed of Richardson and Dunns lakes, Meeker County, showing placement of conservation reserve grassland parcels relative to the flow network.

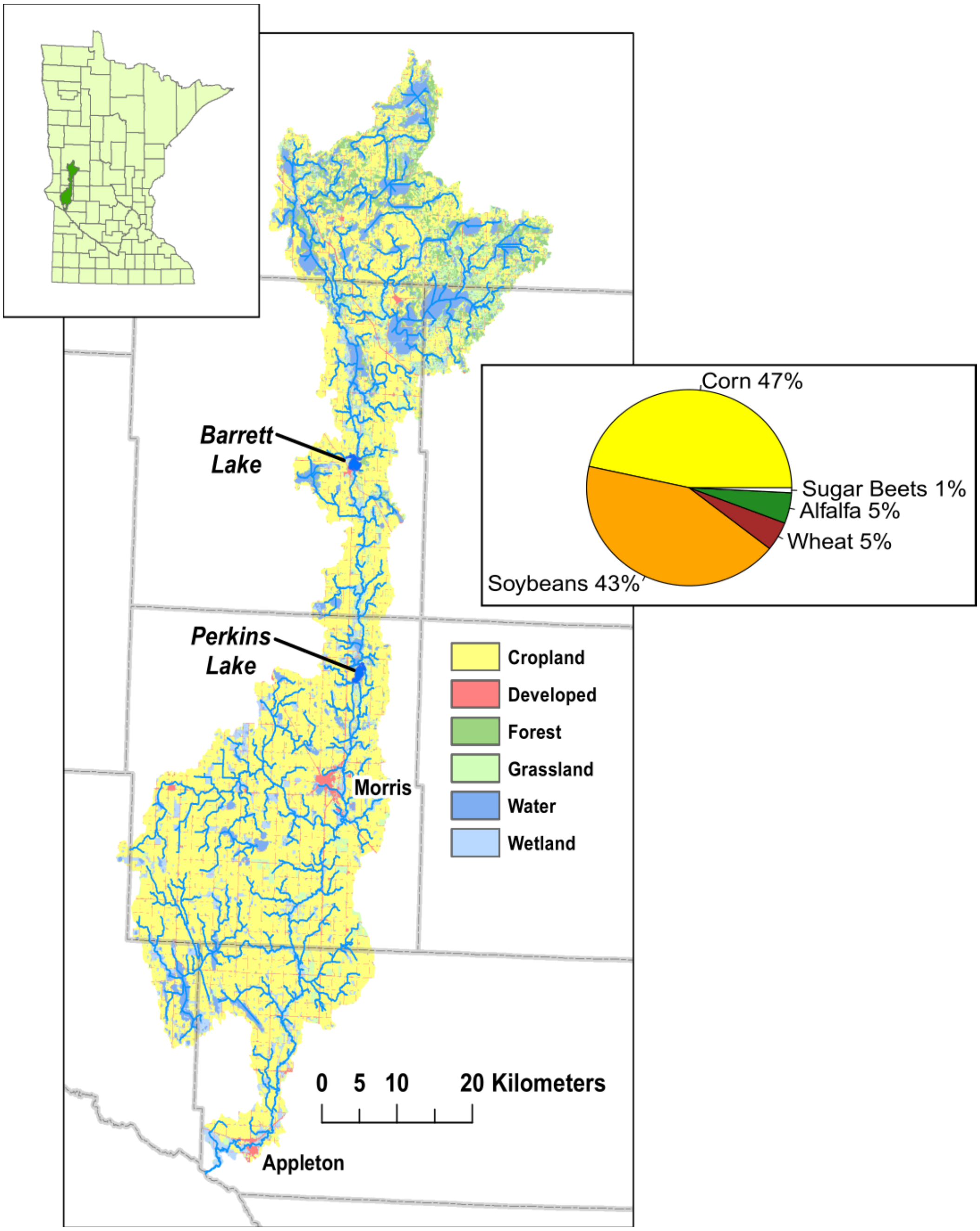


Figure 5. Land cover, stream network, relative crop acreages, and locations of Barrett and Perkins lakes in the Pomme de Terre River Watershed in western Minnesota, for use in a Soil and Water Assessment Tool (SWAT) model to assess landscape erosion and nutrient delivery to the lakes.

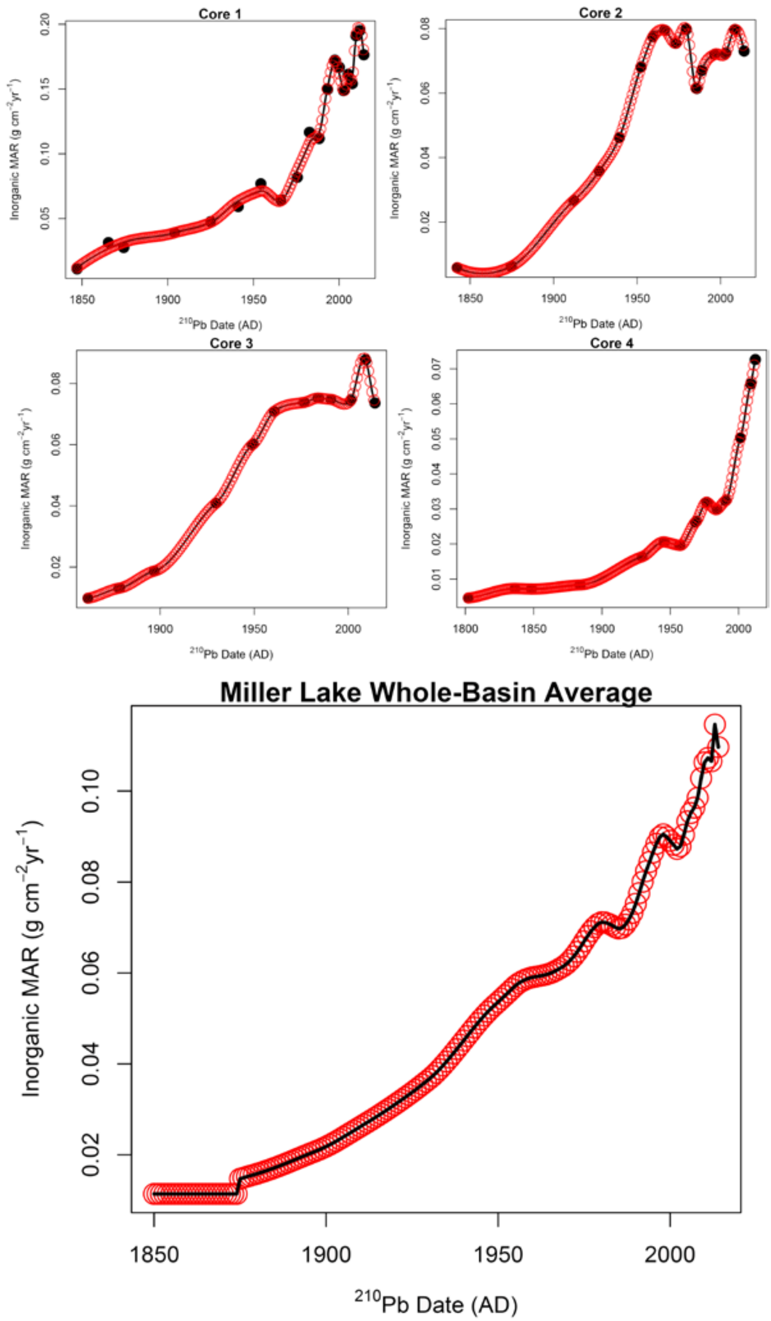


Figure 6. Example from Miller Lake showing how 4 separate cores from a lake (top 4 panels) are combined to present a single whole-basin average (bottom panel) for inorganic sediment accumulation (watershed erosion). Closed black circles are sections dated with ^{210}Pb, open red circles are annual interpolated values between dated sections using a LOWESS smoother. Black line represents the LOWESS smoother model.

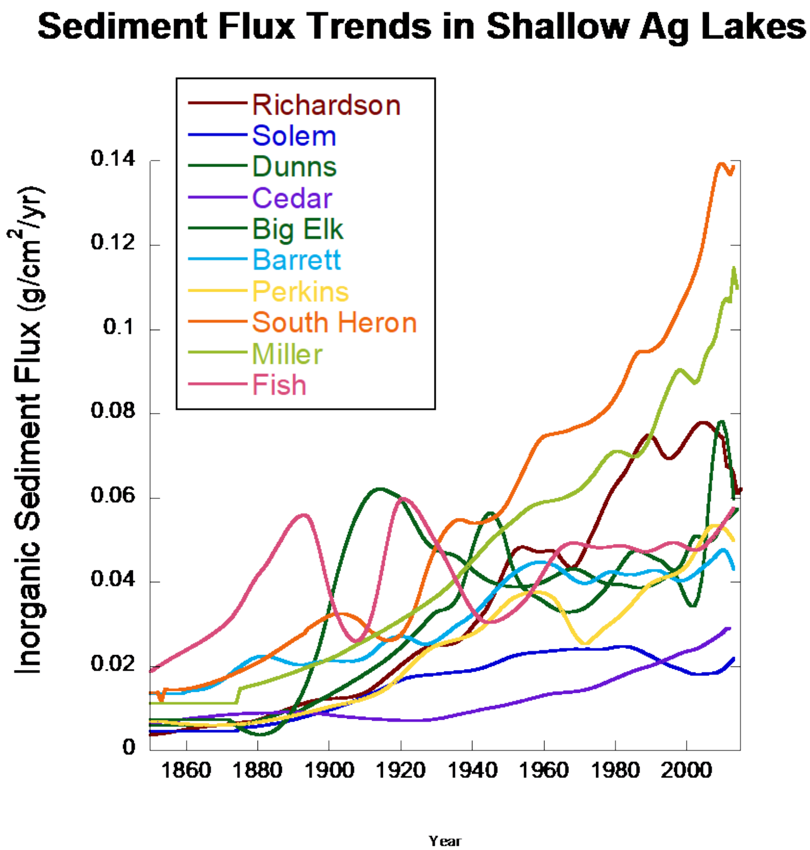


Figure 7. Whole-basin average watershed erosion rates (inorganic sediment flux) for ten of the lakes in this study annualized from 1850 to present. This figure illustrates both the varied trajectory and magnitude of increases in watershed erosion between lakes as well as the congruence of relatively low background (pre-European settlement) erosion rates across systems.

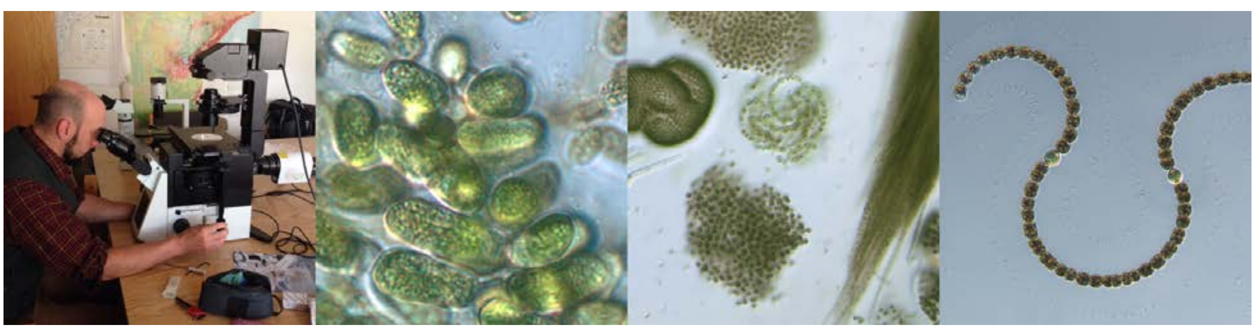


Figure 8. The new CHARM lab at SCWRS is outfitted with microscopes and equipment necessary to analyze cyanobacteria in sediments and water samples. The acquisition of an ELISA system and plate reader allow four cyanotoxins to be screened.

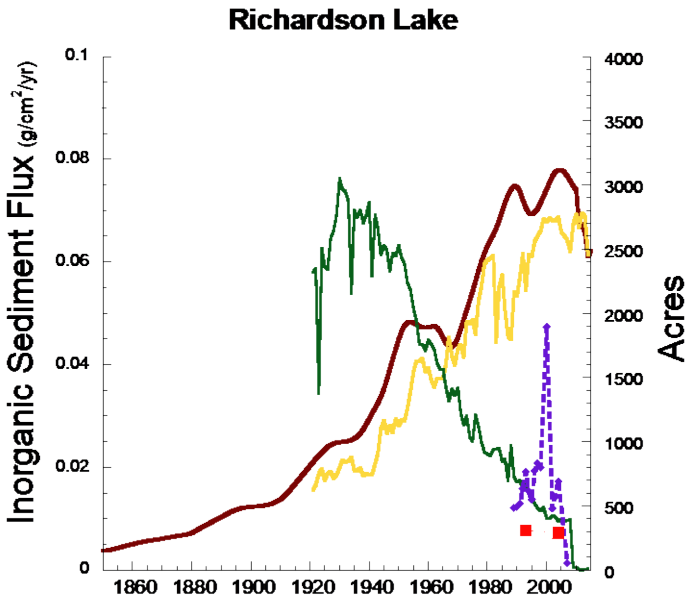


Figure 9. Sediment core record comparing watershed erosion trends (inorganic sediment flux) to land use and management characteristics. These data show rising erosion correlated to the replacement of small grains with more intensively managed row crops and some leveling off or possible decline in erosion coincident with the institution of BMPs in the late 1980's. Brown line represents watershed erosion; green line represents acres of small grains and hay; yellow line represents combined acres of corn, soybeans and sugar beets; purple dashed line and diamonds represent acres of conservation tillage; and red dashed line and squares represent acres in perennial vegetation BMPs.

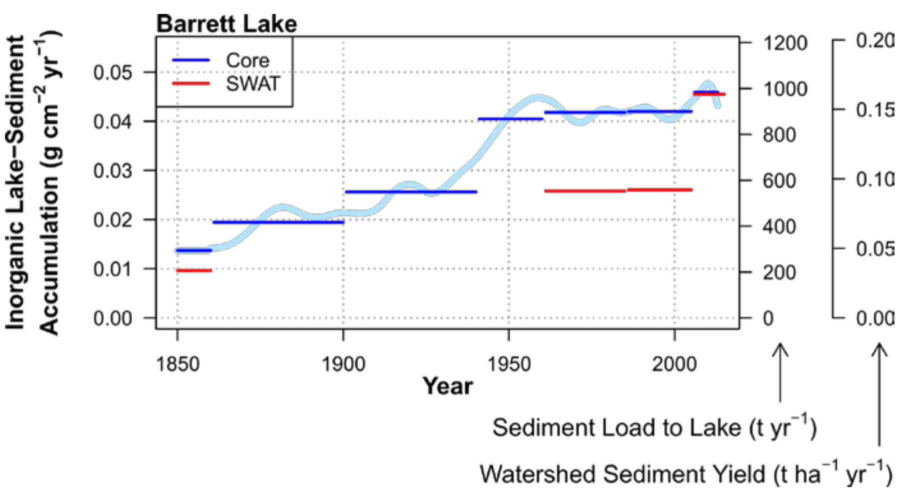


Figure 10. Mass accumulation rate of inorganic sediment for Barrett Lake (Grant County) in the Pomme de Terre watershed, as estimated from multiple sediment cores (aggregated into a single record, light blue line), and from the SWAT watershed model (red). The horizontal bars show average values for four selected time periods: 1850-60, 1961-85, 1986-2005, and 2006-15. Note the consistent range and trend of the two independent measures.

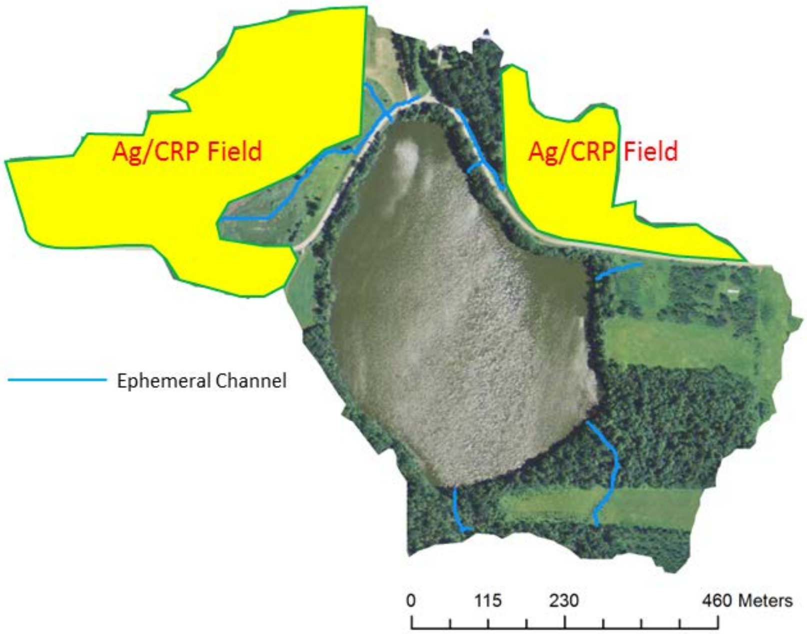


Figure 11. Map of Solem Lake watershed. Yellow areas are the two corn-soybean areas in the watershed; these areas were converted to CRP from 1986 to 2010.

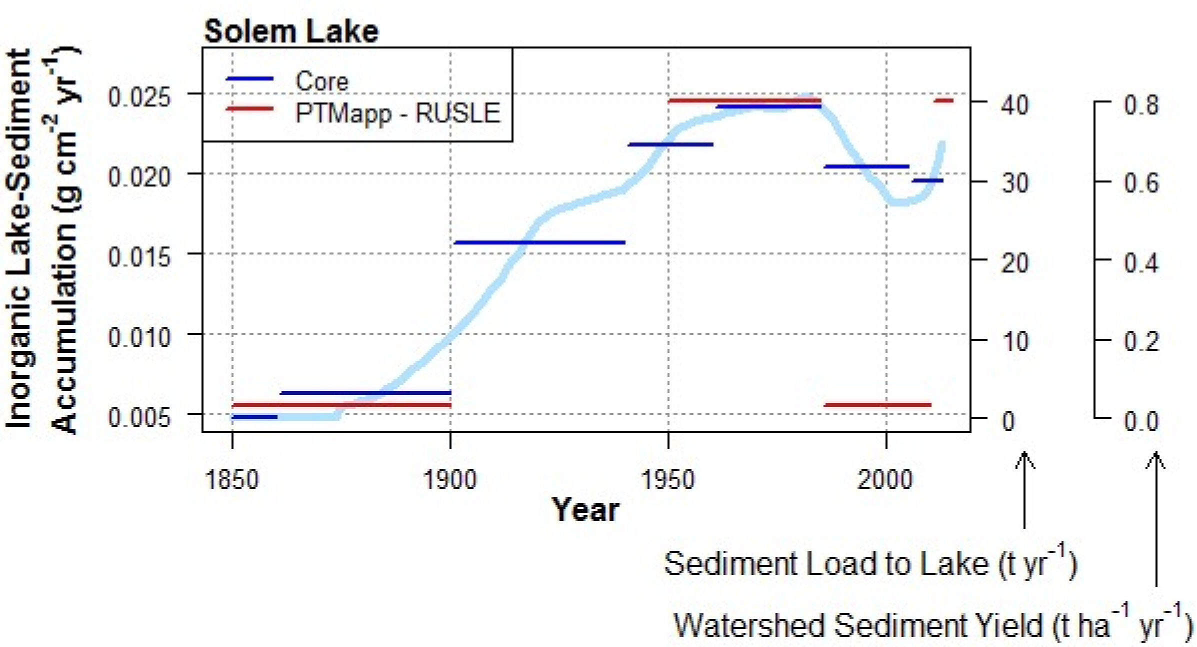


Figure 12. Mass accumulation rate of inorganic sediment for Solem Lake (Douglas County) as estimated from multiple sediment cores (aggregated into a single record, light blue line), and from the PTMapp (RUSLE) annualized watershed model (red). The horizontal bars show average values for four selected time periods: 1850-1900, 1950-85, 1986-2010, and 2010-15. Note pre-1900 and 1950-1985 results match well but erosion from CRP grassland (1986-2010) is substantially under-estimated.

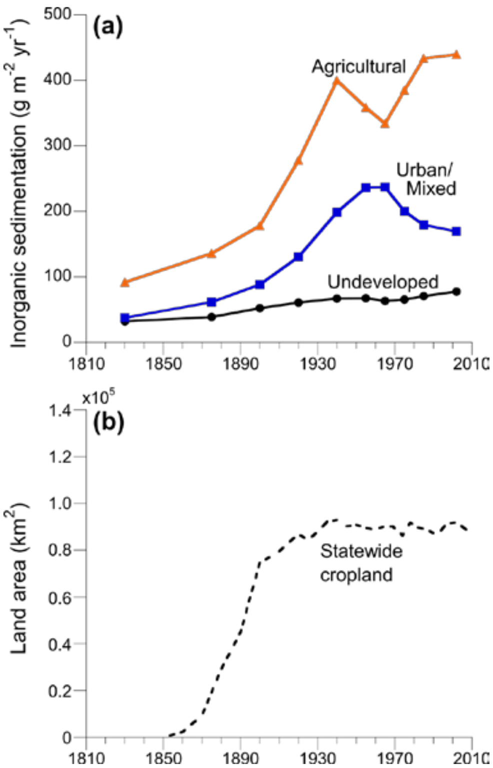


Figure 13. (a) Accumulation rate of inorganic sediment in lakes as a proxy for watershed-scale soil erosion since the time of Euro-American settlement, stratified by dominant land cover. (b) Statewide area of cropland.

NOTES: Data from 142 lakes in core data base archived at the St. Croix Watershed Research Station. Each value represents the median for each category during each decadal time slice.

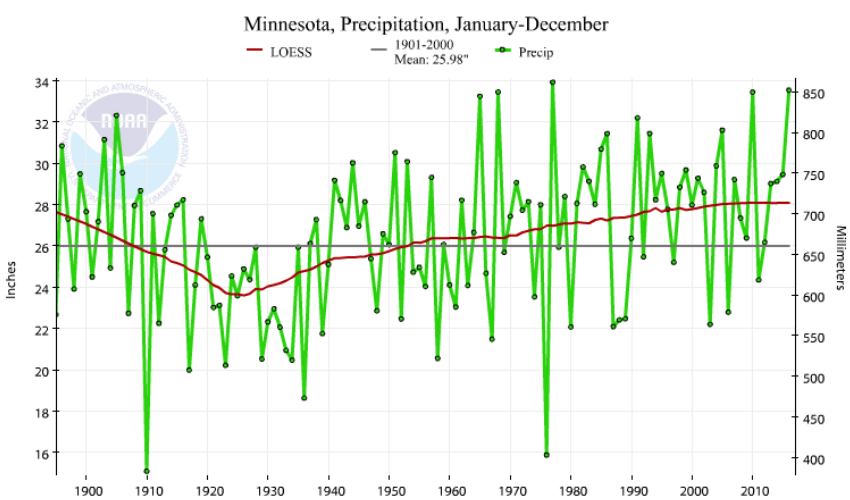


Figure 14. Trend in statewide annual precipitation in Minnesota.

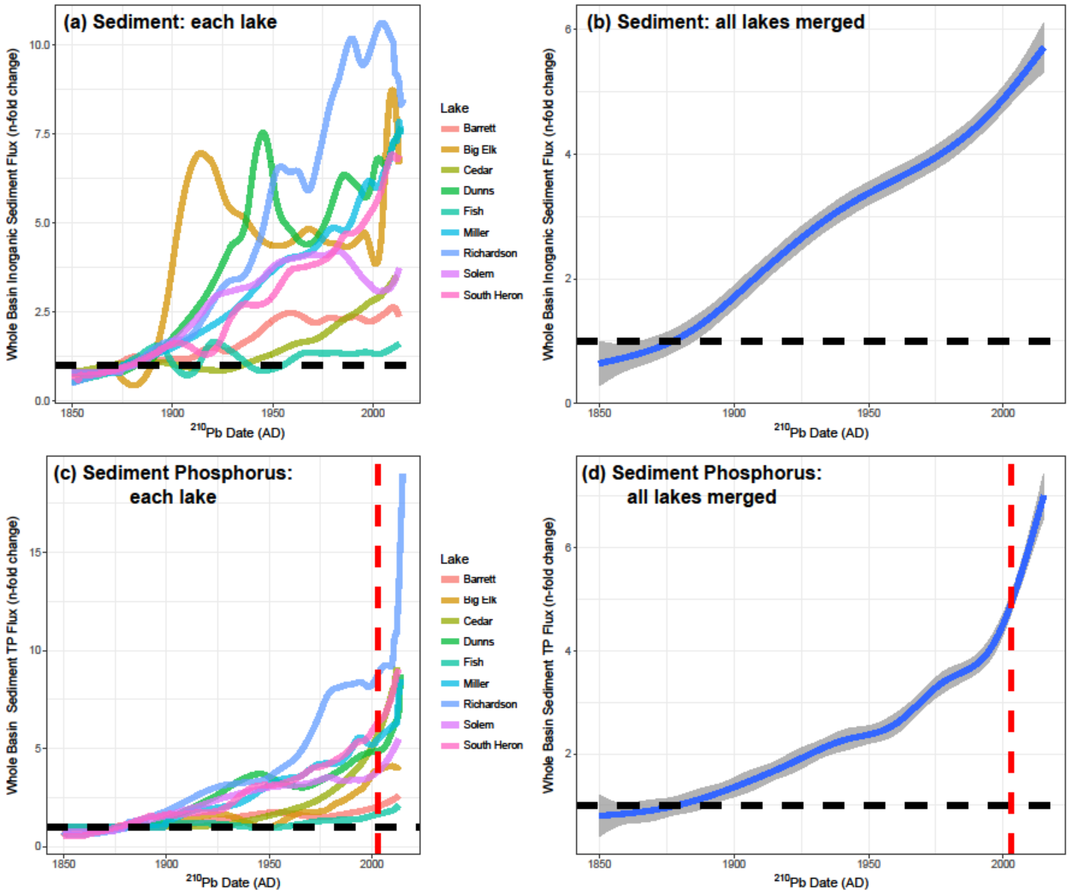


Figure 15. Accumulation rates of inorganic sediment and sediment-bound phosphorus in study lakes since 1850 relative to background rate (1850-1900; horizontal dashed line). (a) Sediment accumulation for individual lakes, showing variability among sites. (b) Sediment accumulation averaged across all lakes. (c) Sediment phosphorus accumulation for individual lakes. (d) Sediment-phosphorus accumulation averaged across all lakes; dashed red line indicates that data from the most recent 15 years is not comparable.

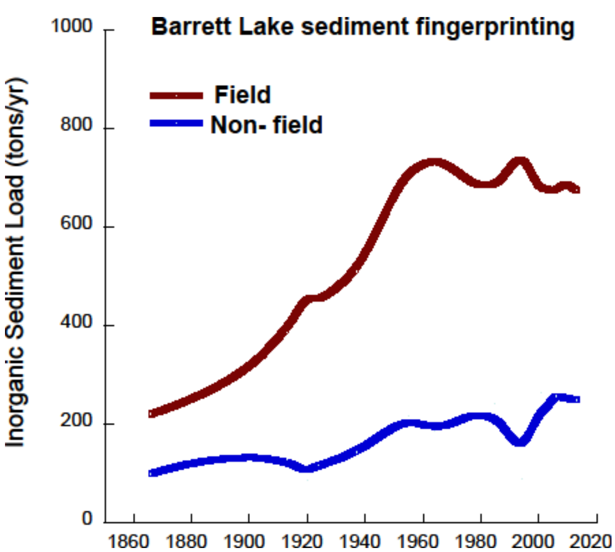


Figure 16. Sediment fingerprinting for Barrett Lake, based on ^{10}Be data.

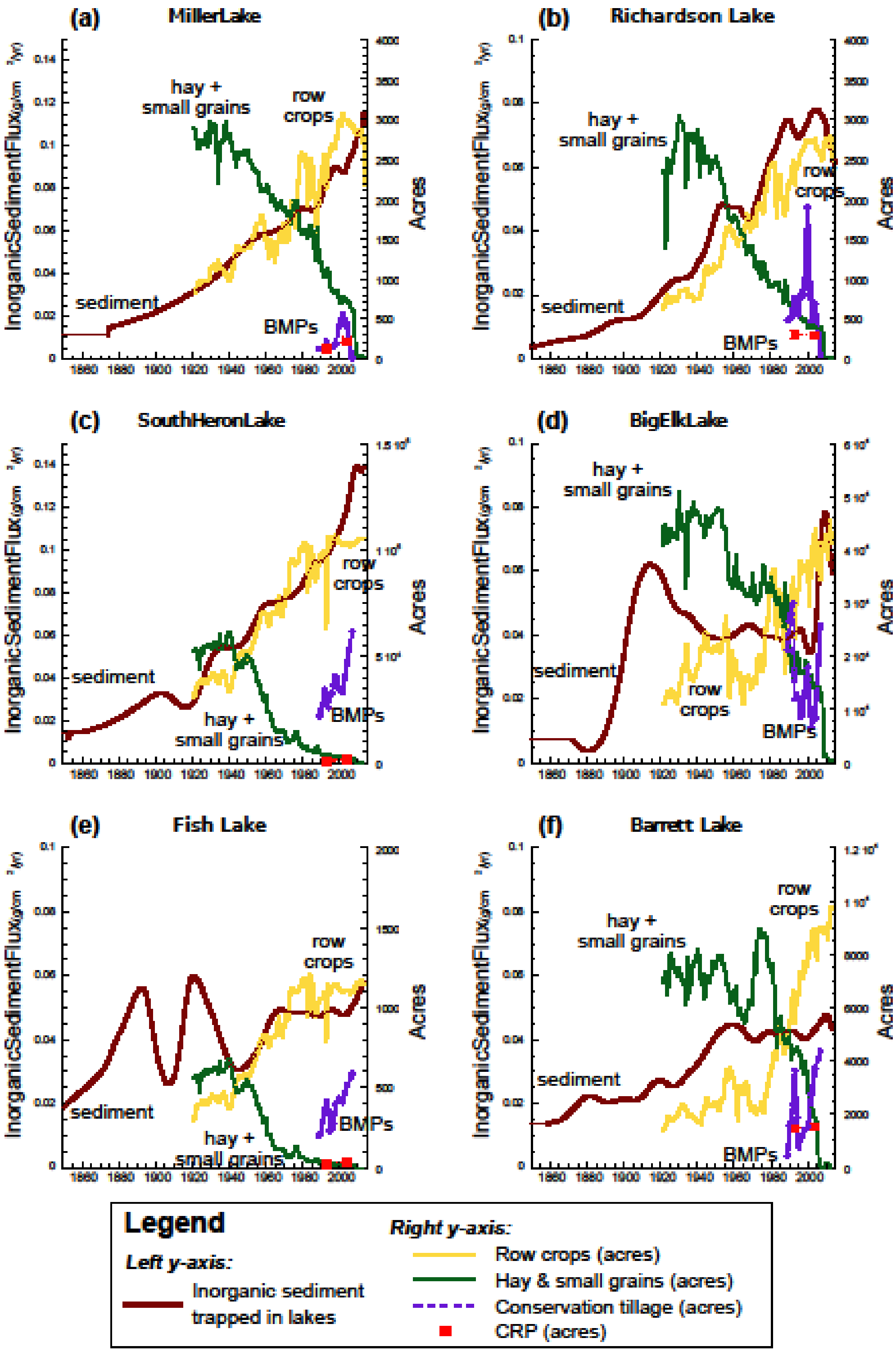


Figure 17. Correlative plots showing rise in sediment accumulation in concert with the rise in row crops and the loss of hay and small grains, along with areas of BMPs, in this case conservation tillage and retirement of lands in CRP.

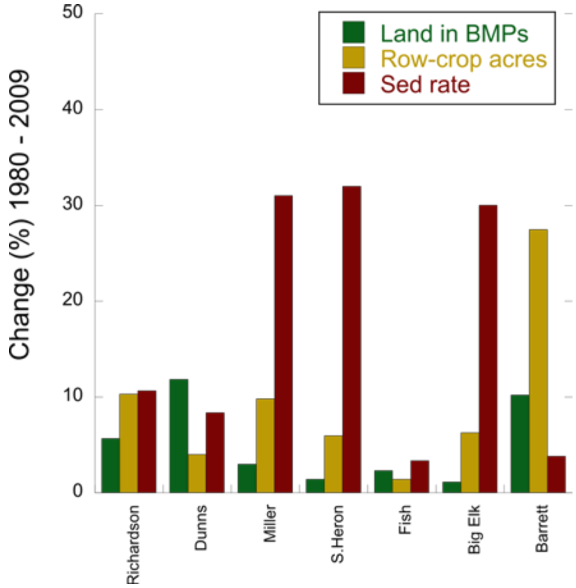


Figure 18. The percent change over 30 years (1980-2009) in sediment accumulation rate for seven selected lakes (red bars) relative to percent changes in area in their watersheds of land in BMPs (green bars) and land in row crops (gold bars). Note that increases in BMPs are commonly cancelled out by increases in row crops.

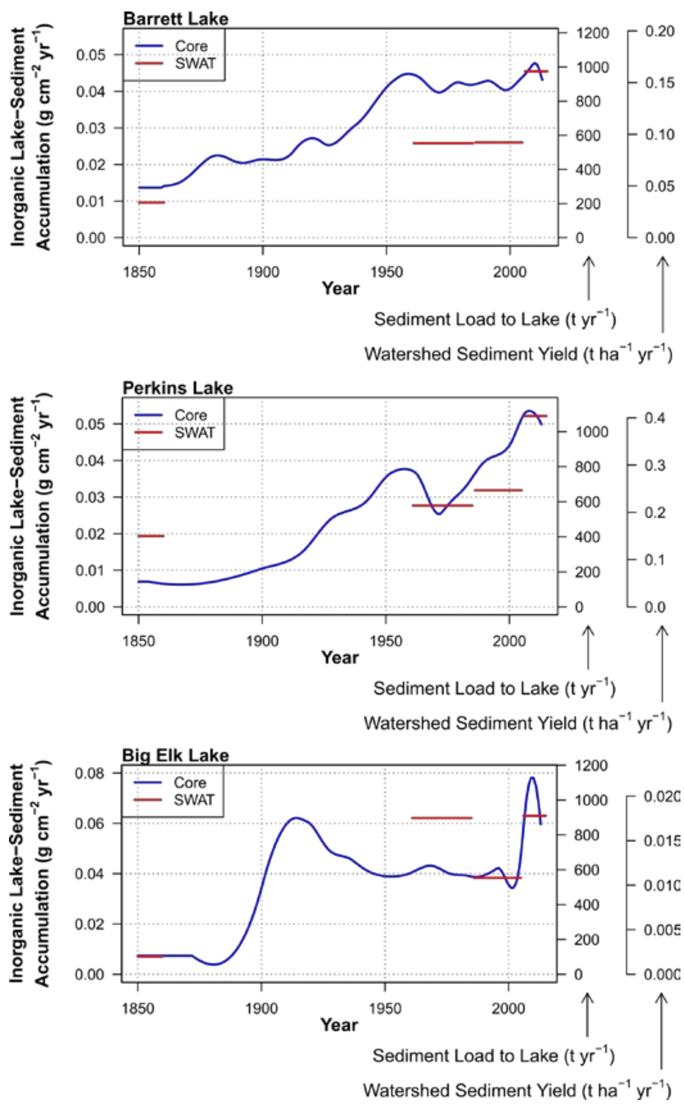


Figure 19. Sediment accumulation rates in three lakes measured in sediment cores (blue) versus estimated by the SWAT model (red segments for four selected time segments).

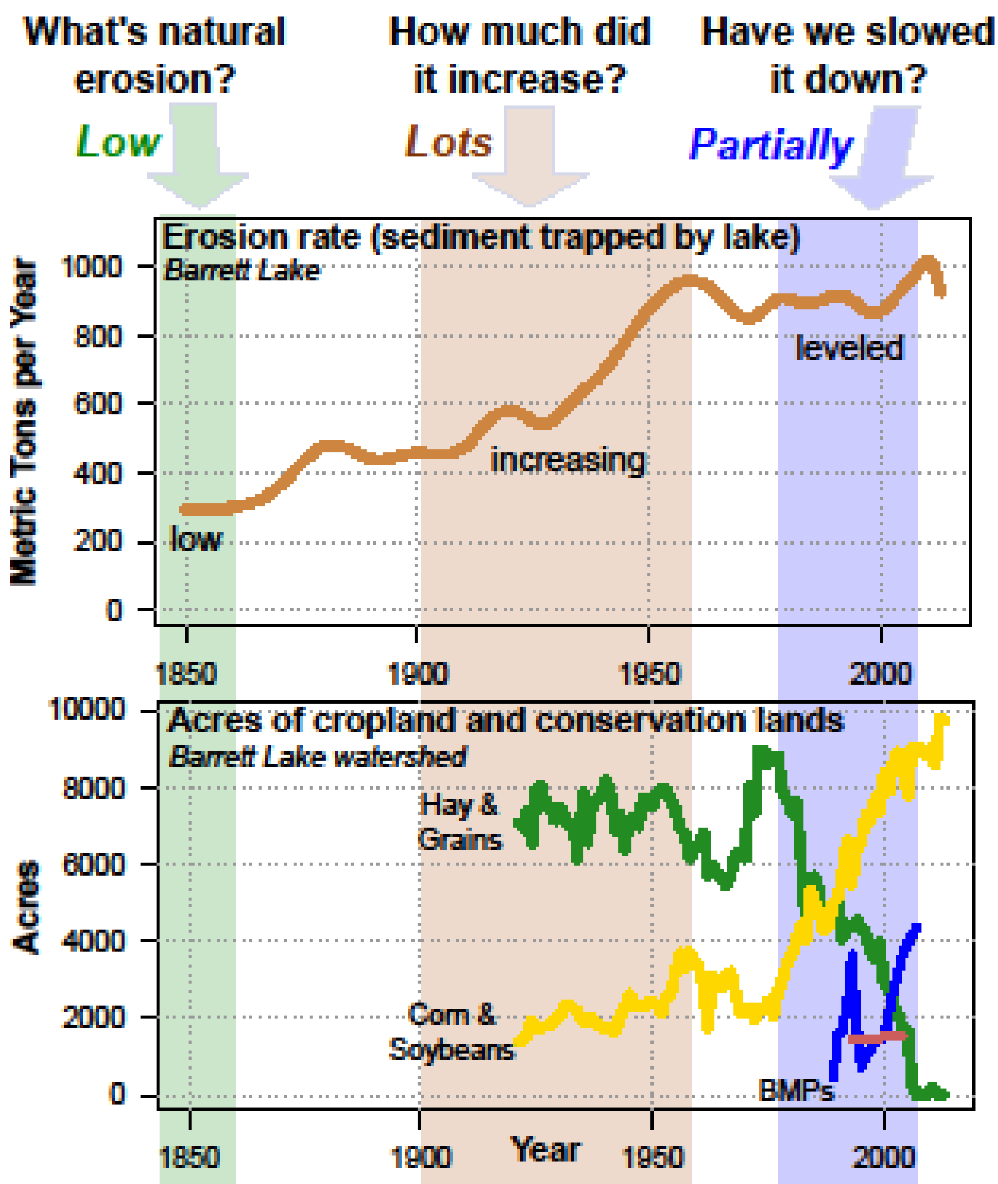


Figure 20. Schematic of overall project conclusions, that nonpoint-source pollution of sediment and nutrients from human activities has increased soil erosion and lake-sediment accumulation at rates many times higher than under natural landscapes. Erosion tends to rise in concert with increased area of row crops, which has partially cancelled out the benefits of implementing BMPs.

Final: **Environment and Natural Resources Trust Fund**

M.L. 2014 Project Budget

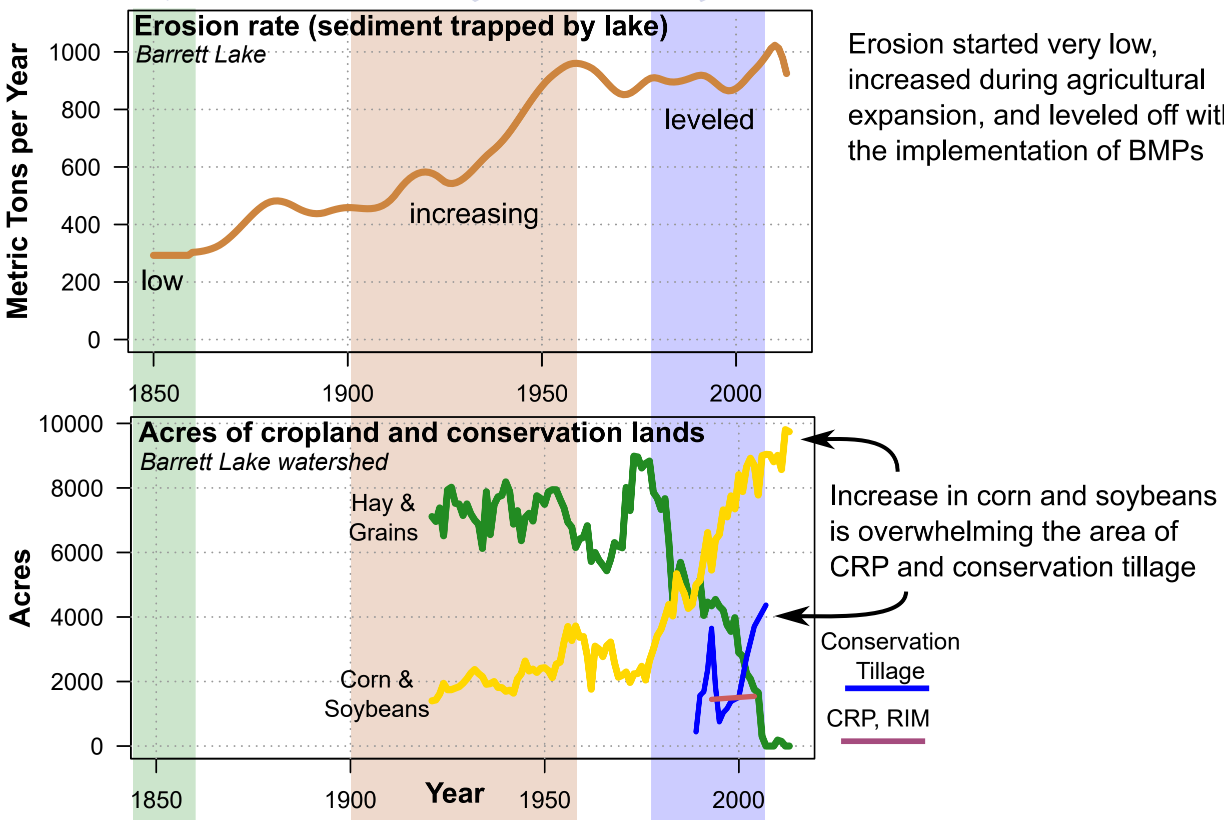
Project Title: Watershed-Scale Monitoring of Long-Term Best-Management Practice Effectiveness
Legal Citation: M.L. 2014, Chp. 226, Sec. 2, Subd. 3(g)
Project Manager: Daniel R. Engstrom
Organization: St. Croix Watershed Research Station, Science Museum of Minnesota
M.L. 2014 ENRTF Appropriation: $ 900,000
Project Length and Completion Date: 3 Years, 30 June 2017
Date of Report: 15 August 2017

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	4-27-17 Activity 1 Budget	Amount Spent	Activity 1 Balance	4-27-17 Activity 2 Budget	Amount Spent	Activity 2 Balance	4-27-17 Activity 3 Budget	Amount Spent	Activity 3 Balance	4-27-17 Activity 4 Budget	Amount Spent	Activity 4 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	**Select new sites, characterize watersheds, & document BMP histories**			**Collect and analyze lake-sediment cores**			**Quantify BMP effectiveness by linking land to water with statistical analyses and modeling**			**Transfer knowledge to resource managers**				
Personnel (Wages and Benefits)	$133,000	$133,000	$0	$148,000	$148,000	$0	$290,771	$290,771	$0	$46,000	$46,000	$0	$617,771	$0
Engstrom, Research Director: Sediment dating; ~8% FTE charged for 3 yr; Salary=77%, Benefits=23% (~$24K)														
Almendinger, Senior Scientist (1 of 3); Watershed analysis, modeling; ~75% FTE for 3 yr; Salary=77%, Benefits=23% (~$199K)														
Edlund, Senior Scientist (1 of 3); Diatom & BG algae analyses; ~75% FTE for 3 yr; Salary=77%, Benefits=23% (~$199K)														
Schottler, Senior Scientist (1 of 3); BMP summary, dating, correlations; ~75% FTE for 3 yr; Salary=77%, Benefits=23% (~$199K)														
Professional/Technical/Service Contracts														
Utah State Univ. (for Be-10 measurements)				$9,639	$9,639	$0							$9,639	$0
Univ. of Regina (for algal pigments & toxins)				$12,000	$12,000	$0							$12,000	$0
St. Olaf University (for C-14 dating)				$6,000	$6,000	$0							$6,000	$0
Univ. of Minnesota (sediment phosphorus analyses)				$28,800	$28,800	$0							$28,800	$0
Equipment/Tools/Supplies														
Field supplies (tubing, tape, sample containers, misc. field gear)				$5,000	$5,000	$0							$5,000	$0
Lab supplies (reagents, glassware, misc. lab supplies)				$31,000	$31,000	$0							$31,000	$0
Data analysis supplies (data acquisition, software)	$3,000	$3,000	$0				$3,000	$3,000	$0	$1,000	$1,000	$0	$7,000	$0
Capital Expenditures Over $5,000														
Equipment: Inverted microscope for algal analysis				$30,000	$30,000	$0							$30,000	$0
Travel expenses in Minnesota				$2,590	$2,590	$0							$2,590	$0
5-10 BMP assessment trips, meet with local resource managers														
5-10 field trips to collect lake-sediment cores														
5-10 trips to present results to local resource managers														
Other -- Analytical Services				$150,200	$150,200	$0							$150,200	$0
Lab analysis of sediment cores: sediment components (organic, carbonate, inorganic fractions); radiometric dating and sediment fingerprinting (Lead-210, Cesium-137); biogenic silica (algal productivity); sediment phosphorus content; particle size; diatom community; blue-green algal fossils.														
COLUMN TOTAL	**$136,000**	**$136,000**	**$0**	**$423,229**	**$423,229**	**$0**	**$293,771**	**$293,771**	**$0**	**$47,000**	**$47,000**	**$0**	**$900,000**	**$0**

M.L. 2014: Watershed Scale Monitoring of Long-Term Best-Management Practice Effectiveness

Project in a Nutshell:
Lakes trap eroded soil and river sediment. Thus lake-sediment accumulation is long-term record of whole-watershed erosion rates, allowing us to answer these questions:

What's natural erosion?	How much did it increase?	Have we slowed it down?
Low	***Lots***	***Partially...***



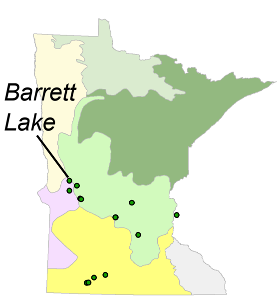
Erosion started very low, increased during agricultural expansion, and leveled off with the implementation of BMPs

Pre-Euroamerican settlement

Agricultural expansion & mechanization

Row crop expansion at same time as BMP adoption

Across the state:



- 57 sediment cores, from
- 14 lake sites, documenting
- 150-year records of erosion, nutrient input, and algal growth

For further information:

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